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HANDLING QUALITIES AND OPERATIONAL PROBLEMS OF A LARGE FOUR-PROPELLER STOL TRANSPORT AIRPLANE

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SUMMARY

A flight investigation was conducted to evaluate the operational problems and handling qualities of a large transport airplane that had been equipped with blowing boundary-layer control on highly deflected flaps, drooped ailerons and control surfaces to give it STOL capabilities. The airplane was capable of landing and taking off over a 50-foot obstacle at distances of less than 1,500 feet and at airspeeds of less than 65 knots. The results of the study have indicated that some standard operational techniques and procedures will have to be revised before full advantage can be taken of the STOL vehicle. The pilot's major control problem at low airspeeds was the large sideslip excursion caused by the unsatisfactory lateral-directional handling qualities. The longitudinal handling qualities were considered satisfactory.

INTRODUCTION

There has recently been an increased interest in aircraft capable of operating out of small confined areas but without the sophistication, or complexity, of the VTOL type aircraft. These vehicles are, for the most part, quite conventional in appearance and retain the high cruise efficiency of the modern turbo-propeller transport. Wind-tunnel investigations (refs. 1 and 2) have shown that deflection of the propeller slipstream by highly deflected BLC trailing-edge flaps and drooped ailerons can produce the necessary lift and drag characteristics to operate airplanes of moderate wing loadings at low airspeeds. The question remains, however, of how low an airspeed is possible before reduced stability and control will make the handling qualities of the airplane unsatisfactory. Reference 3 discusses several problems of the operational and handling qualities encountered in a flight investigation of a twin-engine STOL transport airplane utilizing area suction boundary-layer control on the trailing-edge flaps and drooped ailerons. To extend the study to a transport airplane with four engines and a higher gross weight, an investigation was conducted using a C-130 airplane that had been modified to increase its low-speed capabilities by incorporating blowing boundary-layer control on the trailing-edge flaps, drooped ailerons, elevator, and rudder.

The investigation consisted of evaluating the STOL performance, operational problems, and handling qualities of the airplane.

NOTATION

A_X	horizontal acceleration, $\frac{\text{ft/sec}^2}{g}$
A_Z	vertical acceleration, $\frac{\text{ft/sec}^2}{g}$
b	wing span, ft
BLC	boundary-layer control
C_L	lift coefficient
$C_{L_{max}}$	maximum lift coefficient
C_D	drag coefficient
C_μ	momentum coefficient
F	control force, lb
g	acceleration of gravity, ft/sec^2
T_c'	thrust coefficient
V	airspeed, knots
V_{m_c}	minimum control speed, knots
W	gross weight, lb
α	fuselage angle of attack
β	angle of sideslip, deg
γ	flight-path angle, deg
ζ	damping ratio
δ	control position, deg
δ_a	aileron angle (left - right),[1] deg

[1]Positive angle is defined as trailing edge down.

δ_{a_D}	aileron droop, deg
δ_T	throttle position, percent
θ	pitch angle, deg
$\ddot{\theta}$	pitch angular acceleration, radians/sec^2
τ	time constant, sec
φ	roll angle, deg
$\ddot{\varphi}$	roll angular acceleration, radians/sec^2
ψ	yaw angle, deg
$\dot{\psi}$	yaw rate, radians/sec
ω	undamped natural frequency, radians/sec

Subscripts

app	approach
a	ailerons
c	calibrated
e	elevator
f	flap
r	rudder
s	stall
TD	touchdown

EQUIPMENT AND TEST

Test Airplane

A modified Lockheed C-130B airplane (NC-130B) was used for the tests. A two-view sketch of the airplane is shown in figure 1 and a photograph in figure 2. Table I presents the pertinent geometric data for the airplane.

The NC-130B airplane was designed and built by the Georgia Division of Lockheed Aircraft Corporation under Air Force contract as a STOL test bed. It was powered by four Allison T-56 A-7 turbine engines (normal rating of 3750 ESHP) which drive four-bladed 13.5-foot Hamilton Standard 54H60-63 propellers. The airplane was equipped with shroud-type blowing boundary-layer control on the plain trailing-edge flaps, drooped ailerons, elevators, and the enlarged rudder. The boundary-layer control (BLC) air was provided by two YT-56A-6 engines driving load-compressors mounted on outboard wing pods. Each of the load-compressor engines supplied about 30 pounds of air per second at a maximum pressure ratio of about 3.5. About 75 percent of the air blew over the flaps and ailerons and 25 percent over the tail surfaces. Since there were no power controls on the BLC engines to vary the compressor RPM, the actual output was dependent on the ambient air temperature and pressure. Check valves and crossover ducting allowed the BLC system to be supplied by either or both of the BLC engines.

The flight controls were actuated by an irreversible, fully powered, hydraulic flight control system. Artificial feel was provided by spring cartridges.

The aileron droop mechanism was controlled by a switch on the pilot's console and would only operate at flap deflections greater than 40°. With the switch in the "droop" position, the ailerons would droop or undroop automatically as the flaps passed 40°.

INSTRUMENTATION

Standard NASA recording instruments recorded the angular velocities and accelerations. Airspeed, angles of attack and sideslip, control positions and forces, and attitude angles were recorded on oscillographs. Engine RPM, torque, and turbine inlet temperature were recorded on a photopanel. The free-stream total pressure probe and static orifices were mounted on a one-chord-length, wing-tip boom. To reduce lag effects on the airspeed system, the airspeed and altitude transducers were mounted in the wing tip. The trailing bomb method was used to determine the static pressure error over the speed range with and without the ailerons drooped. The angle-of-attack vane, which was also mounted on the wing-tip boom, was calibrated by determining the differences between attitude, as determined by a sensitive accelerometer and airspeed changes, and the flight-path angle, as determined by a sensitive statoscope. Along with the standard cockpit instrumentation, the pilot was provided an angle-of-attack indicator, a sideslip indicator, and a low-speed airspeed indicator which was operated by the wing-tip transducer.

Test Conditions

The flight tests to document and evaluate handling qualities, lift, drag, and stall characteristics were conducted for the most part at about 5,000 feet altitude, but some lift and drag data was obtained in the landing approach at an altitude of 400 feet or less. Tests were conducted at flap deflections of 0°, 15°, 30°, 60°, 70°, 80°, and 90°. The landing configuration was with 70°

of flap deflection, 30° of aileron droop, and BLC; the take-off configuration was with 40° of flap deflection, 30° of aileron droop, and BLC. The airspeed range for these tests was between 150 and 55 knots. The landing and take-off evaluation flights were made from hard surface runways at Moffett Field, California - elevation 40 feet. A Navy mirror optical landing system was used to establish flight-path angle on many of the landing approach evaluation flights. Take-off gross weight was normally 106,000 pounds and the final landing gross weight was about 97,000 pounds. The center of gravity was 24.6 percent MAC for an average gross weight of 100,000 pounds.

RESULTS AND DISCUSSION

The results of the investigation will be discussed in the following sections: (1) performance, (2) handling qualities, and (3) operational techniques. The lift and drag characteristics including the effect of boundary-layer control are discussed in the appendix.

Performance

Comparison with standard C-130B.- For an economical STOL mission, an airplane must not only be capable of operating at low airspeeds during landing and take-off but also must perform satisfactorily while cruising. The NC-130B resulted from an attempt to extend the low-speed capabilities of an existing airplane with good cruise capability by adding high lift BLC flaps and drooped ailerons. In the following table some of the important gains in low-speed performance achieved by the addition of BLC are compared with a standard C-130B performance at a gross weight of 100,000 pounds (refs. 4 and 5). The NC-130B take-off distances and landing ground-roll distance are measured values. The air distance portion of the total landing distance over 50 feet was computed by the method of reference 6.

	Standard C-130B	NC-130B
Power-off stall speed, knots	79	68
Minimum approach speed (γ=1°), knots	---	63
Landing		
Approach speed, knots	106	67
Ground distance, ft	1450	690
Total distance over 50 feet, ft	3400	1490
Maximum effort take-off		
Take-off speed, knots	79	65
Ground distance, ft	900	775
Total distance over 50 feet, ft	1480	1460
Minimum control speed, knots	94	65

The table shows that although the power-off stall speeds differ by only 11 knots, the selected landing approach speeds differ by 39 knots. Part of the difference can be attributed to the method of selecting approach speeds. The basic C-130 approach speed is based on a value of 1.28 times power-off stall speed, while that for the BLC equipped airplane was based on what the pilots considered a minimum confortable margin from the power-on stall speed and is actually below the power-off stall speed. Therefore, this comparison shows both the differences in performance and operational philosophy required for STOL operation. The operational characteristics will be discussed in a later section of the report. Because of this large difference in approach speed the landing distance was cut in half.

The take-off performance is easier to compare since the maximum effort take-off technique for transport airplanes is basically the same as required for STOL take-offs. The table shows that although the take-off speed for the NC-130B is 14 knots less, the take-off distance is only 125 feet less. The low take-off speeds are accompanied by poor acceleration. This is illustrated in figure 3. Figure 3 shows the variation of distance and acceleration with velocity for various flap deflections. These data were obtained by integration of the measured horizontal acceleration of the airplane in actual take-off ground rolls and corrected to a common gross weight of 106,000 pounds. The data show that if the lift-off speed is 1.2 V_s, power on, the take-off distance is about the same for all flap deflections tested. Reference 1 has shown that to make appreciable gains in take-off distance with high-lift devices, a thrust to weight ratio of 0.5 or greater is required.

In operating from unprepared fields the STOL configuration will show a greater reduction in take-off distance because a larger percentage of the gross weight can be carried by the wings during the ground roll. The one definite advantage of the STOL configuration shown in the table is the relationship of take-off speed to minimum control speed, V_{m_c}. For the standard C-130B, maximum effort take-offs are made 15 knots below V_{m_c}, while for the NC-130B, take-off speeds and V_{m_c} are the same. A lower V_{m_c} was possible because BLC on the control surfaces permitted the ailerons and rudder to be deflected to higher angles.

Operational envelope.- To evaluate the over-all STOL performance, it is necessary to ascertain the airplane's ability to descend at low airspeeds. The operating envelope for the test airplane in the landing configuration is shown in figure 4. The unusual shape of the idle-power curve was the result of the propeller's being against the low pitch stop which gave a negative thrust above 90 knots and a positive thrust below this speed. The operating envelope shows that the stall speed varies 20 knots when going from idle to full power. Only relatively shallow approach angles are possible for airspeeds below 70 knots. The effect of these characteristics on the landing performance is shown in figure 5. The method of references 6 and 7 was used to compute these data. As the approach angle is increased to about 5°, reduction in landing distance over a 50-foot obstacle is possible. As the flight path becomes steeper, the air distance is reduced but, at the same time, ground distance increases because a high touchdown speed is required. It is evident that only a small percentage of the engine power is being used to improve landing performance. If in steep approaches a larger percentage of the thrust could be used to gain lower stall speeds, landing distance could be shortened. However, the operating envelope shows that the airplane has wave-off capability (positive rate of climb) without reducing flap deflection from 70°. This probably would not be the case with higher deflected, more effective flaps. Although a configuration change would complicate the wave-off task, it is not felt that it would be a limiting factor.

Handling Qualities

The handling qualities of the NC-130B in the STOL configuration were changed quite markedly from those of the standard airplane at a corresponding margin above the stall. In fact, the evaluating pilots considered some of the stability and control characteristics to be unsatisfactory. The most seriously affected characteristics were about the lateral and directional axis. The pilot's greatest problem when maneuvering onto and during the final approach, was controlling sideslip angle.

The landing approach configuration ($\delta_f = 70^\circ$, $\delta_{a_D} = 30^\circ$, BLC on) was used for the most part in evaluating and documenting the handling qualities. The brief evaluation in the take-off configuration ($\delta_f = 40^\circ$, $\delta_{a_D} = 30^\circ$, BLC on) indicated little change in the handling qualities between the two configurations.

Control power and damping.- Figure 6 presents the control power and damping variation with airspeed. The control power is shown in terms of initial angular acceleration resulting from a maximum control step input. The damping is in terms of $1/\tau$ for the lateral control and $2\zeta\omega_n$ for the longitudinal and directional control. The variation in control power with airspeed is approximately a function of free-stream dynamic pressure. The following table shows the pilots' ratings[2] of the control power and damping characteristics at an approach speed of about 70 knots. Included in the table is the calculated response of the airplane for comparison with military handling qualities specifications. The response is in terms of the number of degrees of attitude change in 1/2 second for lateral response and 1 second for longitudinal and directional response following a maximum control step input. Although it is recognized that helicopter specifications (Mil-H-8501A, ref. 9) may not apply accurately for the STOL landing approach task, they are the only response and damping specifications available at this time.

Control	Pilots' Ratings	Response	
		NC-130B	Mil-H-8501A
Lateral	5-1/2	1.1°	1.7°
Longitudinal	4	8.0°	3.9°
Directional	4	5.0°	7.1°

[2]Cooper scale, reference 8.

The table shows that the pilots considered control about all three axes to be unsatisfactory (ratings between 3.5 and 6.5) because of the airplane's low response to control inputs. The specified lateral and longitudinal responses are even lower. For lateral control, reference 10 suggested a minimum response of 15° after one second which would have in all likelihood provided satisfactory lateral control for the NC-130B. The results of these tests suggest that a longitudinal response of 10° after one second would be satisfactory. The directional control task is different enough that the helicopter specifications cannot be readily adapted. However, the directional response is still a stringent requirement. Although the directional response of the NC-130B was low, its sideslip response was very high. As will be shown later 15° of sideslip required only 20 percent of the maximum rudder deflection, and correction for asymmetric engine power required only 30 percent; therefore, it appears that at the low airspeeds necessary for STOL operation, rudder requirements for directional response are much higher than those for developing sideslip or for correcting asymmetric power as specified in Mil-F-8785 (ref. 11). More operational experience is needed to determine the type of maneuvering required for this class of vehicle to perform their missions, and more research into the relationship between the control requirements in hover and low airspeeds are required before control power and damping requirements for STOL operation can be adequately defined.

The over-all control characteristics were downgraded to 6-1/2 because of the poor mechanical characteristics of the flight controls. Figure 7 shows the spring and friction characteristics of the lateral and longitudinal control system. The high friction resulted in poor centering characteristics and increased control forces. The directional control system was impossible to document in a similar manner because of the very unusual and undesirable mechanical characteristics; therefore, the rudder position and force relationship are shown in time history form. These data show the breakout force and the lack of definite control position to force relationship. The experience with this airplane and the C-134 (ref. 3) bears out the importance of achieving good mechanical control characteristics for STOL airplanes. Low friction forces such as those specified in Mil-H-8501A are felt to be necessary.

<u>Static longitudinal stability</u>.- Figure 8 presents the variation of the elevator position with angle of attack for two engine powers. These data show that the airplane has positive angle-of-attack stability but becomes unstable at high angles of attack with high engine powers. The pilots considered the stability in the approach satisfactory (numerical rating of 3). The unstable region at high angles of attack at high engine power made control difficult, and along with the low control power in all three axes, at speed less than 60 knots, limited the maximum angle of attack with maximum power. Reference 2 pointed out that high downwash angles at the horizontal tail could be expected at high thrust coefficients and is believed to be responsible for the instability. Although the wind-tunnel report indicated that downwash angle sufficient to stall the fixed horizontal stabilizer could be expected, no evidence of tail stall was noted.

<u>Trim changes due to flaps and thrust</u>.- Since there are fairly large airspeed changes associated with lowering or raising the flaps in STOL operation, trim change data were obtained during an actual take-off and landing. Figure 9(a) shows the elevator angle required for trim variation with flap deflection for the

take-off condition (flaps going up) with maximum power and increasing airspeed and for the landing condition (flap going down) with idle power and decreasing airspeed. Figure 9(b) shows the trim variation with flap deflection at about 68 knots and at power for level flight. The control forces that accompany the elevator angle changes required for trim were less than the 10 pounds specified in Mil-F-8785 and were rated satisfactory by the pilots.

Figure 10 represents the trim change with power for a constant angle of attack and for a constant airspeed. The data show that at a constant angle of attack, the elevator angle change required for trim was small although speed changed 18 knots. Since landing approaches were made at nearly constant angles of attack, the pilot considered the trim change with power to be satisfactory. The fact that airspeed changed from 83 to 64 knots, a 40 percent decrease in free-stream dynamic pressure, with little change in elevator deflection, indicates that the moment due to thrust change was almost equal to the moment due the combined change in dynamic pressure and downwash. This means that when the throttle is advanced with elevator fixed, the initial response is a nose-down moment due to thrust, which results in a rapid increase in airspeed and little change in flight angle. The pilots considered the response to a thrust change to be satisfactory.

Dynamic longitudinal stability.- The dynamic longitudinal stability of the airplane was characterized by a highly damped short period and a divergent phugoid at the landing approach speed. Figure 11 shows a time history of an elevator pulse at about 70 knots. An analysis showed that the motion was approximated by a system having a short period of 6.5 seconds per cycle and a damping ratio of 1.0, and having a divergent long period, or phugoid, with a period of 22 seconds per cycle (double amplitude in 19 seconds). The pilots considered the short-period characteristic satisfactory. The phugoid was objectionable to the pilots because of the large changes in airspeed and attitude and was easily excited by either elevator or throttle motions.

Static lateral and directional characteristics.- The aileron position, rudder position, and roll angle required for trim at various airspeeds and at two engine powers are shown in figure 12. These data show that the control deflection required for trim is small and supports the pilot's opinion that the lateral and directional control required for trim was not a problem as it was in the YC-134A (ref. 3). The large amount of scatter in the sideslip data was considered normal and emphasizes the problem of sideslip control at low airspeed.

The static directional stability in terms of rudder position with sideslip angle, β, is shown in figure 13. These data show a stable and linear variation to a sideslip angle of 15° with only 20-percent rudder. However, the pilots reported that at about 18° of sideslip, the yawing-moment variation with sideslip became unstable and sideslip increased without additional rudder. This is a characteristic of the basic C-130B airplane (ref. 4). The presence of the instability was of concern to the pilot because of the large sideslip excursions which developed when maneuvering at low airspeeds. Mil-F-8785 requires linearity to only 15°, but more stringent sideslip angle requirements may be necessary in STOL operation (15° of sideslip is required to compensate for 15 knots crosswind at 60 knots airspeed). The decrease in side force with sideslip angle, as speed was decreased, gave a sensitive relationship of bank angle to sideslip. The lower curve of figure 13 shows that in steady sideslips, 15° of sideslip required only 5° of bank angle. Figure 14 compares the bank angle for 5° of sideslip obtained on a C-130B (ref. 12) over a wide airspeed range with the results of this investigation. The data emphasize that the low side-force gradient is a result of the low airspeed and not the STOL configuration.

Lateral-directional dynamic characteristics.- From the pilot's evaluation of the landing approach it was determined that the major problem area of this airplane was its lateral and directional dynamic characteristics. The pilots found that large sideslip excursions accompanied maneuvering in the landing approach and control was difficult when the angle of sideslip was allowed to build up to any appreciable value. Therefore, the pilot was required to refer constantly to the sideslip indicator in the cockpit. The problem can be illustrated by referring to figure 15 which shows time histories of the response of the airplane following a rudder-fixed, left aileron pulse. As the airplane banked to the left about 12°, the yaw rate was to the right, opposite to the turn, because of the adverse yaw produced by aileron deflection. As soon as the ailerons were neutralized, the airplane turned in the direction of the bank. At the same time, sideslip developed rapidly as bank angle increased. Opposing this buildup in sideslip is the directional stability, which tends to reduce the sideslip as turn rate is increased. The low directional stability resulted in a large-amplitude long-period oscillation. The oscillation had a 12-second period and is lightly damped (damping ratio of 0.1). Figure 16 shows the dynamic behavior of the airplane with aileron fixed following a rudder pulse and better illustrates the lightly damped long-period directional oscillation. Since the dihedral effect is low, the amplitude of the roll oscillation which accompanies the directional oscillation is small. Some roll is evident because of roll due to rudder deflection and yaw rate. The mechanical characteristics of the rudder, which were discussed earlier, made it very difficult for the pilot to damp out these oscillations with rudder, or coordinate the controls to take out the cross-coupling effects. As a result, the sideslip varied constantly during an approach. Since Mil-F-8785 does not adequately define the lateral-directional requirements for satisfactory handling qualities in STOL operation, there is a need for study of this problem to determine what are acceptable characteristics, what parameters will require upgrading, and whether such fixes can be accomplished aerodynamically, or through a stability augmentation system.

Stalling characteristics.- An evaluation at 6,000 feet of the stalling characteristics with approach power showed that as stall is approached, there is a decrease in lateral control power. At the angle of attack for wing buffet, lateral control is almost zero. Therefore, if there is any roll rate as stall is approached, the airplane will roll off; but if the airplane approaches the stall with wings level, and low sideslip, the airplane has no tendency to roll or yaw at stall. It was not possible to fly the airplane to angles of attack much more than $C_{L_{max}}$ because of loss of control. Recovery from stall, where there was a roll or yaw, required reducing the angle of attack and diving the airplane to an airspeed where the control again became effective.

Stall evaluations at maximum power with both take-off ($\delta_f = 40^{\circ}$, $\delta_a = 30$ BLC-on) and wave-off ($\delta_f = 70^{\circ}$, $\delta_a = 30$ BLC-on) configurations showed little difference due to configuration. The high power stalls were characterized by a reduction in longitudinal stability to a point of becoming unstable and a large reduction in control power but no buffet. The stall speed was considered that at which airspeed did not change appreciably as angle of attack was increased. This was essentially $C_{L_{max}}$. The following table gives the stall speeds and angles of attack for stall for various configurations:

$\delta_f - \delta_a$	Measured				Estimated		
	Power	V_s	α_s	Alt	V_s, knots	Power	Alt
40 - 30	0.85 max	60	12	6000	55	Max	Sea level
70 - 30	.85 max	56	12	6000	48	Max	Sea level
70 - 30	.3 max	63	11	6000	58	0.3 max	Sea level
70 - 30	Idle	73	11	6000	68	Idle	Sea level

Since altitude had such a large effect on stall speed, the values determined from extrapolated data (see appendix) are also shown.

The pilots considered the stall characteristics satisfactory. However, they considered the stall warning and lateral control at the stall objectionable. With engine power the airplane exhibited only mild wing buffet which occurred within a couple of knots of the stall. The loss of lateral control at the stall afforded the pilot no means of controlling any roll that might occur at the stall without a loss in altitude to decrease angle of attack and increase airspeed.

Operational Techniques

Landing (general).- It was discovered early in the landing evaluation that a vehicle of this type does not conform well to conventional traffic patterns. All the pilots were impressed with the length of time required to conduct the approach, especially when the final landing configuration was established prior to turning onto the base leg. The time required to complete an instrument approach was even longer, since with the particular ILS system the glide slope was intercepted about 8 miles from touchdown.

The requirement to maintain tight control in an ILS approach in combination with the aircraft's undesirable lateral-directional characteristics resulted in noticeable pilot fatigue. Two methods were tried to reduce the time spent in the STOL (final landing) configuration. The first and more obvious was suitable for VFR patterns and consisted of merely reducing the size of the pattern, flying the downwind leg at about 800 feet and close abeam, then transitioning to the STOL configuration and reducing speed before turning onto the base leg. Ample time and space were available for maneuvering, even for a vehicle of this size. The other procedure consisted of flying a conventional pattern at high speed (120 knots) with 40° of flap to an altitude of about 500 feet, and then performing a maximum deceleration to the approach angle of attack using 70° flap and 30° of aileron droop with flight idle power. Power was then added to maintain the approach angle of attack while continuing to decelerate to the approach speed. This procedure reduced the time spent in the approach and generally expedited the operation. Figure 17 presents a time history of slowing down from 125 knots to about 70 knots. The most noticeable adverse effect of this technique was the departure from the original approach path in order to slow down. This effect would compromise its use on a conventional ILS glide path.

Final approach technique.- The technique used on the final approach was to maintain a constant angle of attack by referring to the cockpit-mounted indicator while controlling flight-path angle with power. The reason angle of attack was considered a better reference parameter than airspeed is best illustrated by figure 4 which presents steady-state flight-path angle as a function of velocity at various values of constant engine thrust. Cross plotted on this figure are lines of constant angle of attack which correspond to each combination of thrust and airspeed in steady unaccelerated flight. It can be seen that not only does the stalling speed vary with engine power, but also the angle of attack associated with a particular value of airspeed. In addition, since both the engine power and BLC effectiveness vary as a function of temperature and density altitude, these parameters also affect the stalling speed, so that it was actually possible to approach at speeds below the corresponding power-on stall speeds observed at altitude. Because of these factors, it was impractical to use airspeed as a primary flight instrument during the landing approach when maximum performance was desired. It was noted, however, during the stall tests, that the indicated angle of attack at which the stall occurred was essentially independent of configuration, power setting, BLC pressure, gross weight, or altitude. This then provided a more reliable indication of the margin from the stall.

Minimum approach speed.- Over the range of approach angles which were of greatest interest, from about 2° to 5°, an angle of attack of about $2\text{-}1/2^\circ$ was used. This corresponds to a minimum confortable approach speed of 67 knots on a 3° approach path at 100,000 pounds gross weight as indicated in figure 4. The resulting $9\text{-}1/2^\circ$ angle-of-attack margin from the stall appeared to provide ample protection against gusts, trim changes (due to power), and inadvertent pilot inputs. In addition, it was adequate for normal maneuvering and provided sufficient flare capability to arrest the sink rate before touchdown. During the steeper approaches (i.e., more than 5°), it was desirable to maintain a greater flare capability in order to assure the pilot that sink rate could be reduced to a reasonable rate before touchdown. The approach angle of attack was therefore reduced, and the corresponding approach and touchdown speeds were somewhat higher. The pilots felt that considerably more skill and judgment were required to execute the flare from these steeper approaches, particularly when maximum performance was desired. An attempt was made to improve the performance by flying steep approaches at about $2\text{-}1/2^\circ$ angle of attack, and using engine power to flare. The initial results, however, were not satisfactory. If the increase in power were delayed to the point where the aerodynamic flare was normally commenced, the pilot inevitably overcontrolled and considerable floating was experienced. If the power was increased earlier, the flight-path angle was decreased and the resulting total distance over a 50-foot obstacle was the same as for a shallower approach.

To achieve maximum STOL performance, it is desirable that a constant flight-path angle be established prior to reaching the obstacle height. For this purpose, the Navy's mirror optical landing system proved to be a highly useful tool. No problems were encountered in either acquiring or tracking the flight path provided by this device. Unfortunately, the particular system used was incapable of being elevated to more than 4° and therefore could not be used during the steep approaches. It is felt, however, that the instantaneous flight-path information provided by this, or a similar device, would be most useful to the pilot during a steep approach, particularly in unfamiliar terrain or adverse weather conditions.

Effect of engine failure on approach characteristics.- Reference 3 has indicated the severe operating limitations imposed on a twin engine STOL aircraft when one engine fails during the approach. A similar investigation conducted on the NC-130B revealed that much less severe limitations prevailed during three-engine approaches with this airplane. The critical engine could be either number 1 or 4, and the minimum control speed was limited not by directional control power, but rather by the lateral control power required to maintain trimmed flight. The control deflections required to trim are indicated in figure 18 as a function of airspeed for the wave-off or go-around configuration (70° flap, 30° aileron, no. 1 engine windmilling, and numbers 2, 3, and 4 at about 2800 horsepower). This and similar data for other power settings were used to determine the three-engine operating envelope presented in figure 19. At the intermediate and steep approach angles, there was only a slight increase in the minimum approach speed which resulted from the loss of lift from the windmilling propeller. At shallow approach angles or during a go-around, however, the pilot would have to maintain a margin above the minimum control speed to insure some degree of lateral control. No attempt was made to determine the required margin.

Although the approach itself, with one engine inoperative, presented no great problem to the pilot, the characteristics during flare and touchdown were somewhat less favorable. Indicated in figure 18 are the sideslip and/or bank angle required to balance the asymmetric side force due to the inoperative engine. Since during a STOL approach engine power must be retained until touchdown, this asymmetry can not be eliminated prior to landing as it can in a more conventional approach. The pilots felt it was easier to use bank angle to maintain straight flight with near zero sideslip; however, the pilots' natural tendency to relax the lateral control force during the flare would cause the aircraft to drift toward the side of the runway in the direction of the inoperative engine. As a consequence of this characteristic in combination with the poor control of sideslip mentioned previously, the pilots elected not to actually touch down during any of the simulated three-engine approaches. More experience with this type of behavior is required to accurately assess the magnitude of this problem. In discussing the effects of an engine failure, it seems advisable to describe the behavior of the aircraft with partial BLC failure. Although no accurate quantitative measurements were made, it was estimated that if one BLC engine were lost during the approach, an altitude loss of about 200 feet would be incurred before the pilot could re-establish himself on the original flight-path angle. There was no control problem associated with this failure; however, the minimum approach speed would have to be increased by about 10 knots.

Flare and touchdown.- Although the rate of descent was not high, even the shallower approaches required some flare. Because of the low angle of attack used during the approach, the airplane had to be rotated before touchdown to prevent the nose wheel from contacting the runway before the main gear. For the same reason, the airplane could not be landed at speeds much greater than the normal touchdown speed. Both of these problems are illustrated by figure 20 which represents a side view of the airplane during a low pass down the runway at about 85 knots. Since an appreciable amount of lift was dependent upon engine power, it was imperative that the throttles not be retarded abruptly prior to touchdown. If the main gear contacted the runway at any appreciable sink rate, they tended to bounce while the nose wheel remained on the ground. This, in conjunction with the cycling of the antiskid brakes, produced a porpoising effect which caused discontinuous longitudinal deceleration. As soon as the ground was contacted, however, the propellers were positioned at full reverse pitch while the BLC supply was shut off simultaneously. This placed a considerable portion of the aircraft's weight on the main wheels and produced maximum braking effectiveness.

Wave-off or go-around.- With all engines operating no problem was encountered in waving off under any of the conditions tested (maximum gross weight of 106,000 lb). In fact, as soon as full power was obtained it was possible to initiate flap retraction with no loss in altitude. The wave-off capability with one engine inoperative, however, was much more critical. In addition to the lateral control problem previously mentioned, the climb-out capability was considered marginal. This is shown in figure 19 where it can be seen that a climb angle of only 1-1/2° could be attained at 100,000 pound gross weight at an approach speed of 68 knots. Although a positive climb angle could be achieved at this approach speed, it was found desirable to partially reduce the flap deflection to reduce drag so that a positive climb angle plus an increase in airspeed could be achieved.

Take-off.- Although only small gains in take-off performance were possible in the STOL configuration, as pointed out in the performance section, take-off speeds were as low as 61 knots. To decrease the take-off distance, higher thrust to weight engines would be required; but the take-off speed would not change appreciably. Therefore, it was felt that the operating problems of STOL take-off could be evaluated. It was determined from the evaluation that the STOL take-off procedures were essentially the same as for a normal take-off except for the low airspeed at lift-off. The upper boundary of the operating envelope for the airplane in the take-off configuration is presented in figure 21. The boundary indicates that the stall speed was 55 knots with a steady-state angle of climb of 9° at a take-off speed of 65 knots. The pilots chose 65 knots as the best take-off speed from an operational and handling qualities point of view. This provided a 10-knot margin above the power-on stall speed and was at or above the minimum control speed.

Since take-off speeds are much below the best climb speed for the airplane in the clean configuration, the airplane must be accelerated over a wide speed range after take-off. The STOL take-off configuration has high drag; therefore, it is advantageous to reduce the flap deflection as soon as possible after take-off. One procedure that accomplished the desired results was to put the flap lever in the up position as soon as rotation was complete. Figure 22 shows a comparison of the time history of climb-outs using the early flap retracting procedure with one leaving flaps at the take-off position. It can be seen that although the altitude is about the same at the end of 30 seconds, the difference in airspeed is about 60 knots. The rate of flap retraction in the test airplane was not considered to be optimum. More operating experience with varying flap retraction rates would be required to determine the optimum.

The characteristics of the airplane with an outboard engine windmilling in the take-off configuration was essentially the same as in the landing configuration discussed in an earlier section. As shown in figure 21, the V_{m_c} was 65 knots and was determined by near maximum lateral control required for trim. At speeds near V_{m_c}, the loss of an engine reduced the climb-out capability of the airplane by about 4°, but was considered by the pilots to be satisfactory for an emergency condition. Engine cuts during actual take-offs were not performed nor were three-engine take-offs. It is felt that because of the poor lateral-directional handling qualities and the very undesirable mechanical characteristics of the control system, an engine cut during take-off or even three-engine take-offs would be dangerous.

Concluding remarks.- The flight control system of an airplane in STOL operation must have good mechanical characteristics (such as low friction, low break-out force, low force gradients) but positive centering and no large nonlinearities.

In order to aid in establishing general handling qualities criteria for STOL aircraft, more operational experience is required to help define such items as (1) minimum airport pattern geometry, (2) minimum and maximum approach and climb-out angles, (3) maximum cross wind during landings and take-offs, and (4) all-weather operational limits.

SUMMARY OF RESULTS

The following are the results of this investigation of the STOL characteristics of the NC-130B airplane:

1. With the landing configuration of 70° of flap deflection, 30° of aileron droop, and boundary-layer control, the test airplane was capable of landing over a 50-foot obstacle in 1,430 feet at 100,000 pounds gross weight. The approach speed was 72 knots and the flight-path angle 5° for minimum total distance. The minimum approach speed in flat approaches was 63 knots.

2. Take-off speed was 65 knots with 40° of flap deflection, 30° of aileron droop and boundary-layer control at a gross weight of 106,000 pounds. Only small gains in take-off distance over a standard C-130B airplane were possible because of the reduced ground roll acceleration associated with the higher flap deflections.

3. The airplane had unsatisfactory lateral-directional handling qualities resulting from low directional stability and damping, low side-force variation with sideslip, and low aileron control power. The poor lateral-directional characteristics increased the pilots' workload in both visual and instrument approaches and made touchdowns a very difficult task when the critical engine was inoperative.

4. Neither the airplane nor helicopter military handling quality specifications adequately define stability and control characteristics for satisfactory handling qualities in STOL operation.

5. Several special operating techniques were found to be required in STOL operations:

(a) Special procedures are necessary to reduce the time in the STOL configuration in both take-offs and landings.

(b) Since stall speed varies with engine power, BLC effectiveness, and flap deflection, angle of attack must be used to determine the margin from the stall.

6. The minimum control speed with the critical engine inoperative (either of the outboard engines) in both STOL landing and take-off configurations was about 65 knots and was the speed at which almost maximum lateral control was required for trim. Neither landing approach nor take-off speed was below the minimum control speed for minimum landing or take-off distance.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Nov. 6, 1962

APPENDIX

LIFT AND DRAG CHARACTERISTICS

The lift and drag characteristics for the airplane in the STOL landing and take-off configurations are presented in figure 23. The data for low altitude (below 300 feet) have been extrapolated above an angle of attack of about 4° using the shape of the lift and drag curves obtained at 5,000 feet altitude. The change in lift was the result of a change with altitude of C_μ and T_c' for a fixed power control setting. The effect of flap deflection on the lift characteristics is shown in figure 24. These data show that the optimum flap deflection was 70° with a drop off at higher flap deflections. The fact that the flap lift tends to level out at flap deflections of about 60° indicated that the BLC system did not maintain complete flow attachment on the flap. Tuft studies of the flow characteristics showed that above about 40° flap deflection, regions of separated flow were evident at about midchord of the flap behind the outboard engine. Table II shows that the nozzle gap behind the outboard engine is about 15 percent less than behind the inboard engine which undoubtedly contributes to the poor flow. Because of the limited time available for the tests, no attempt was made to optimize the BLC system. However, a modification was accomplished to cover the large cutouts on the flaps' radius that opened up at flap deflections above 60°. This modification significantly improves flap lift at the higher flap deflections as shown in figure 25 and emphasizes the importance of maintaining a clean flap radius free of cutouts or other discontinuities.

In an endeavor to determine whether a higher C_μ would significantly increase the flap lift, a brief test was flown with the BLC ducts to the tail blocked to increase the BLC air to the wing. Unfortunately, 70° flap deflection was the maximum that could be used for these tests because of the cover-plate installation. Figure 26 shows that the C_L for zero angle of attack was increased by a C_L of 0.8 at the maximum engine power at 6,000 feet altitude. Also shown on figure 26 is the variation of lift coefficient with the estimated value of momentum coefficient. The nozzle characteristics and duct pressure variations were not calibrated; therefore, the flight values of momentum coefficient are considered only estimated values (±20 percent); they are shown here only to establish the trend. The shape of the curve indicates that the expected gains in C_L with increased C_μ based on unpublished small-scale tests were achieved.

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TABLE I.- GEOMETRIC DATA

Wing	
Total area, sq ft	1745.5
Span, ft	132.69
Mean Aeordynamic chord, ft	13.71
Taper ratio	.52
Aspect ratio	10.09
Angle of incidence, deg	
Root	0
Tip	-3.0
Airfoil section	
Root	NACA 64A318
Tip	NACA 64A412
Dihedral, (lower surface), deg	2.3
Flap	
Area, sq ft	287.8
Span (each side), ft	
Inboard	11.3
Outboard	26.2
Deflection (maximum), deg	90.0
Chord (percent wing chord)	25.0
Aileron	
Area, sq ft	110.0
Span (each side)	18.8
Chord (percent wing chord)	28.0
Droop, deg	30.0
Travel (maximum from wing chord line)	
Normal, deg	
Up	30.0
Down	19.0
Drooped, deg	
Up	30.0
Down	60.0
Horizontal tail	
Area, sq ft	543.0
Span, ft	52.7
Airfoil section	NACA 23012
Elevator area, sq ft	154.0
Elevator travel (maximum), deg	
Up	49.0
Down	38.5
Vertical tail	
Area, sq ft	330.0
Span, ft	23.1
Airfoil section	Modified NACA 64A016
Rudder area, sq ft	98.6
Rudder travel (maximum), deg	±60.0

TABLE II.- BLC NOZZLE HEIGHTS

Surface	Percent span	Nozzle height, in.
Inboard flap	0 - 46.3 46.3 - 100.0	0.071 .075
Outboard flap	0 - 22.2 22.2 - 45.3 45.3 - 67.5 67.5 - 89.4 89.4 - 100.00	.070 .064 .060 .056 .045
Aileron	0 - 16.6 16.6 - 42.8 42.8 - 71.4	.046 .044 .034
Elevator	0 - 29.2 29.2 - 53.5 53.5 - 77.1 77.1 - 100.0	.031 .037 .034 .030
Rudder	0 - 24.7 24.7 - 50.1 50.1 - 75.0 75.0 - 100	.065 .060 .048 .034

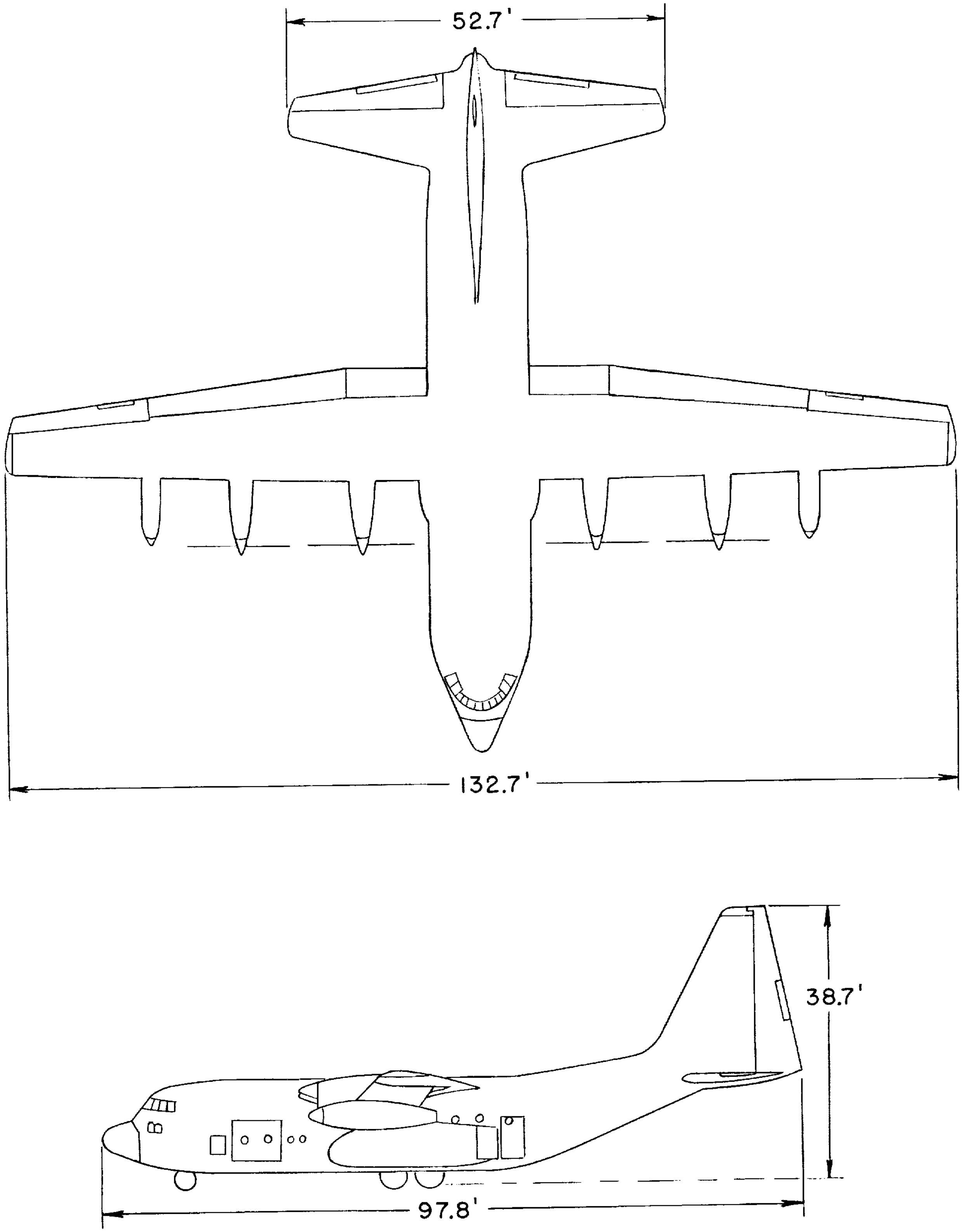

Figure 1.- Sketch of test airplane.

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Figure 2.- Photograph of test airplane with flaps deflected 70° and ailerons drooped 30°.

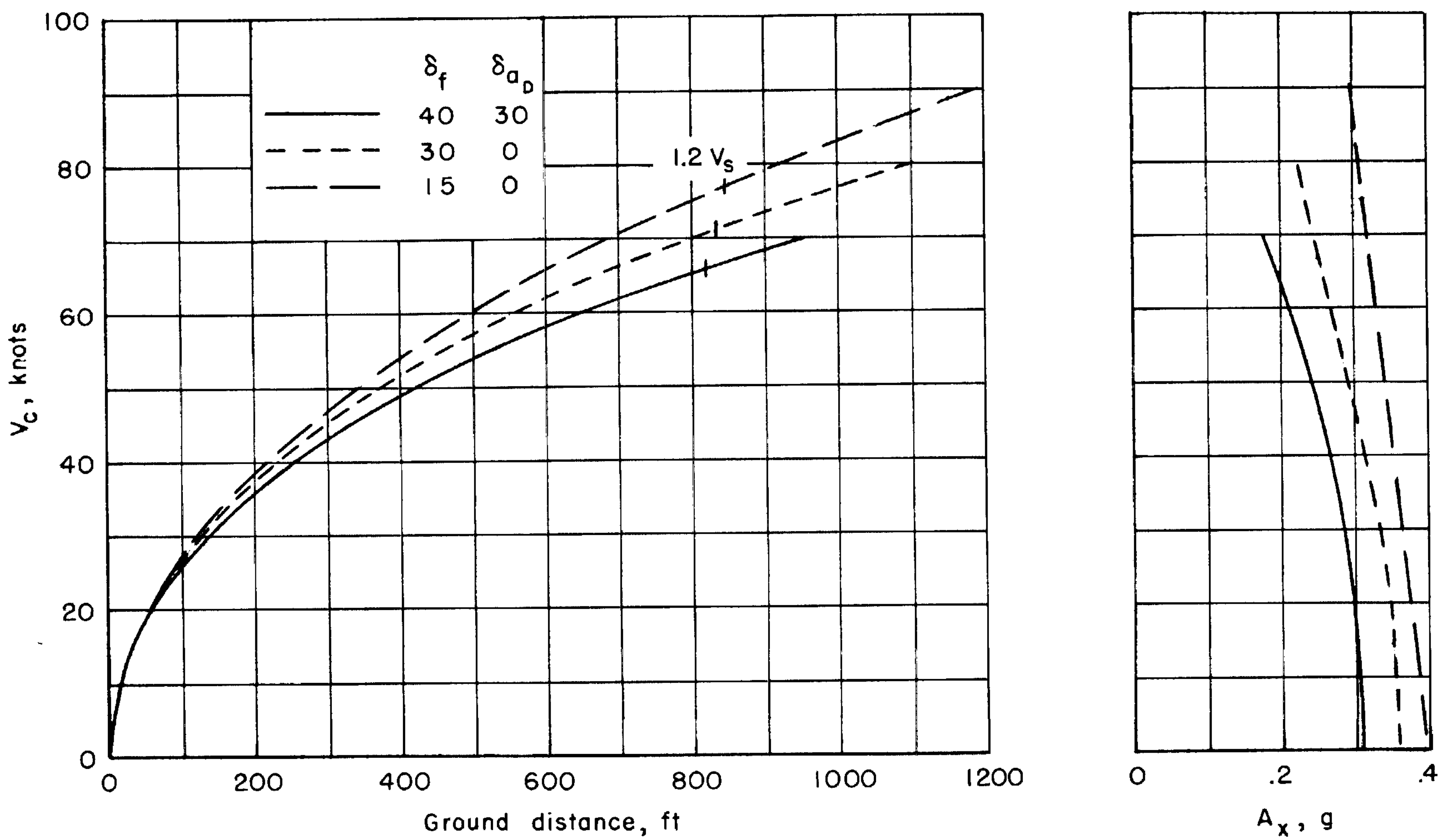


Figure 3.- Take-off characteristics at various flap deflections; gross weight = 106,000 lbs, BLC on.

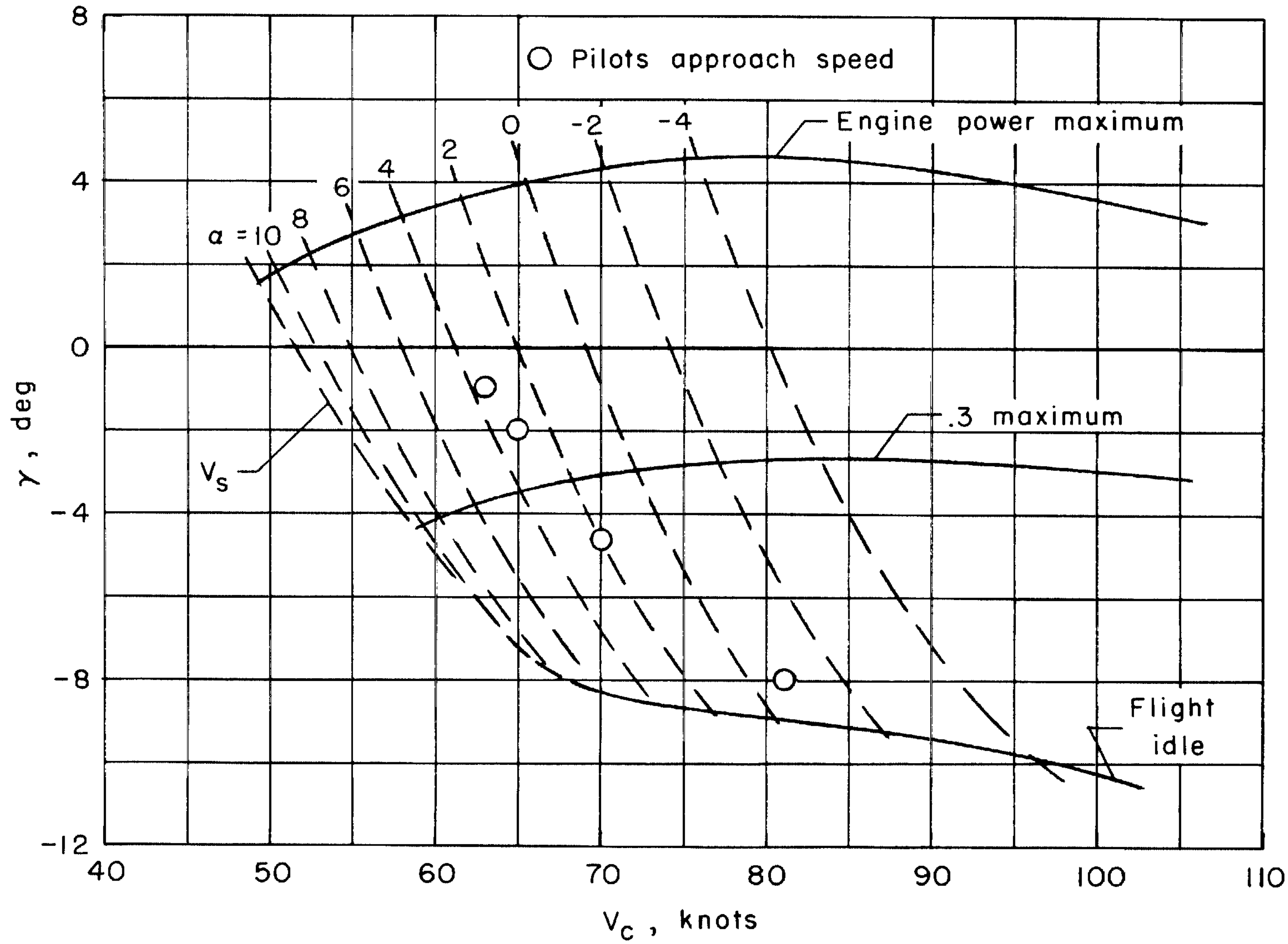


Figure 4.- Operational envelope in the landing configuration; $\delta_f = 70^\circ$, $\delta_{a_D} = 30^\circ$, BLC on, gross weight 100,000 lb, sea-level standard day.

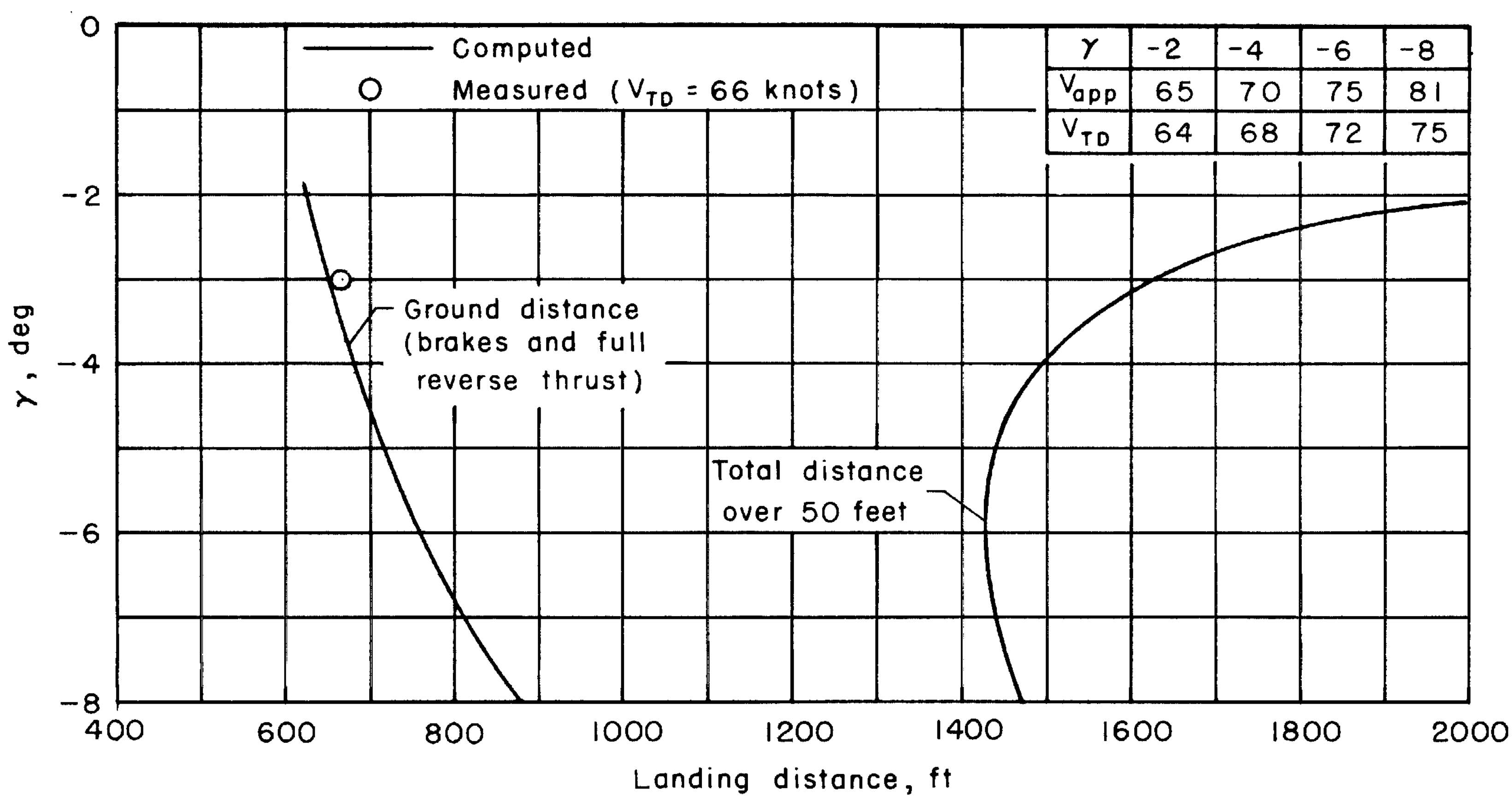


Figure 5.- Variation of landing distance with flight path angle; $\delta_f = 70^{\circ}$, $\delta_{a_D} = 30^{\circ}$, BLC on, gross weight 100,000 pounds, sea-level standard day.

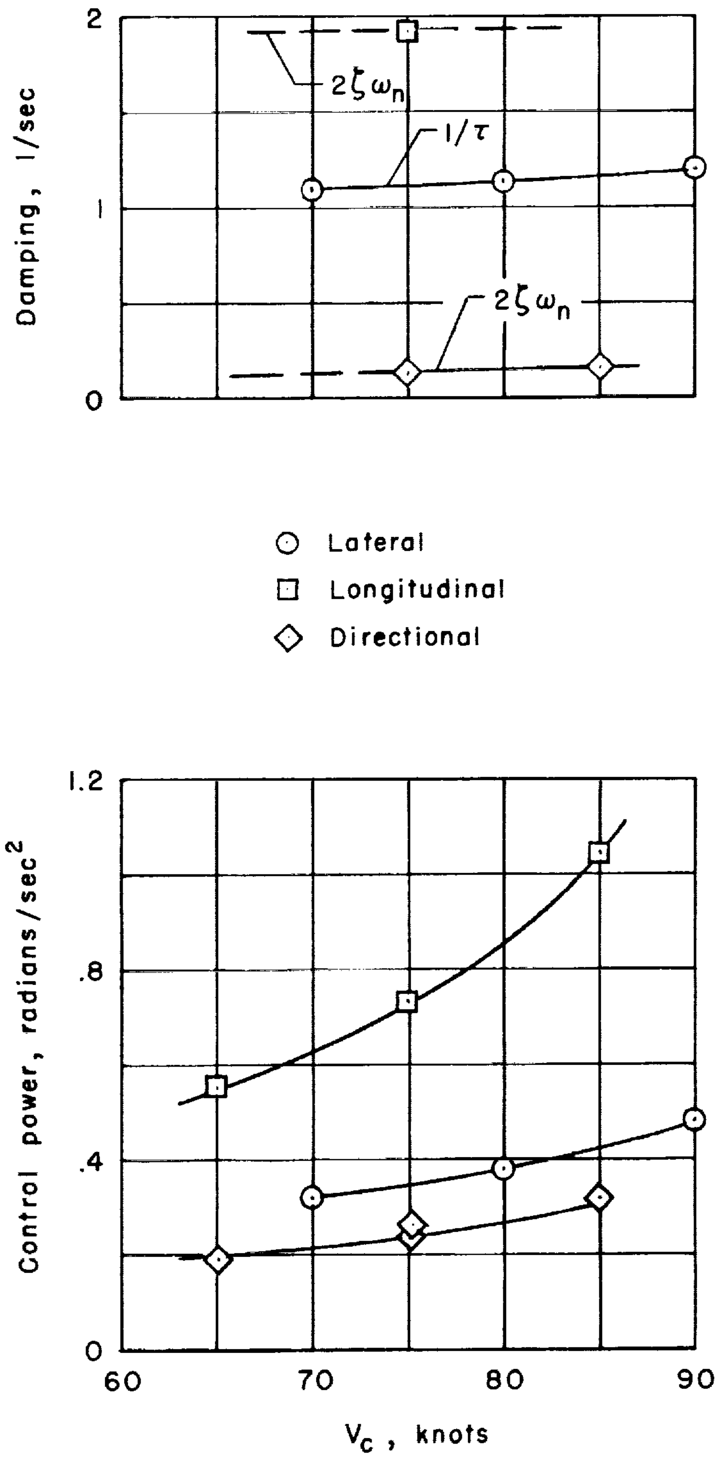
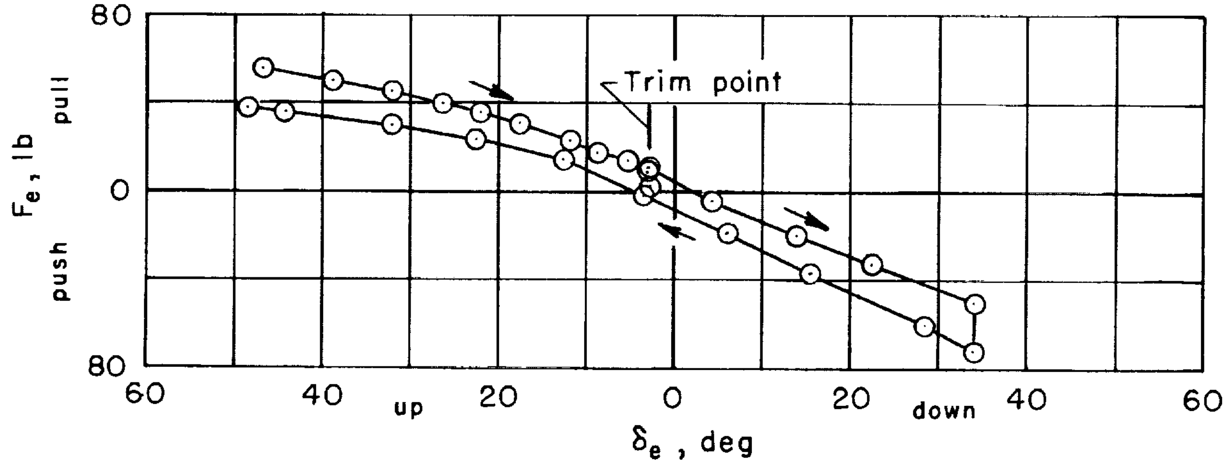
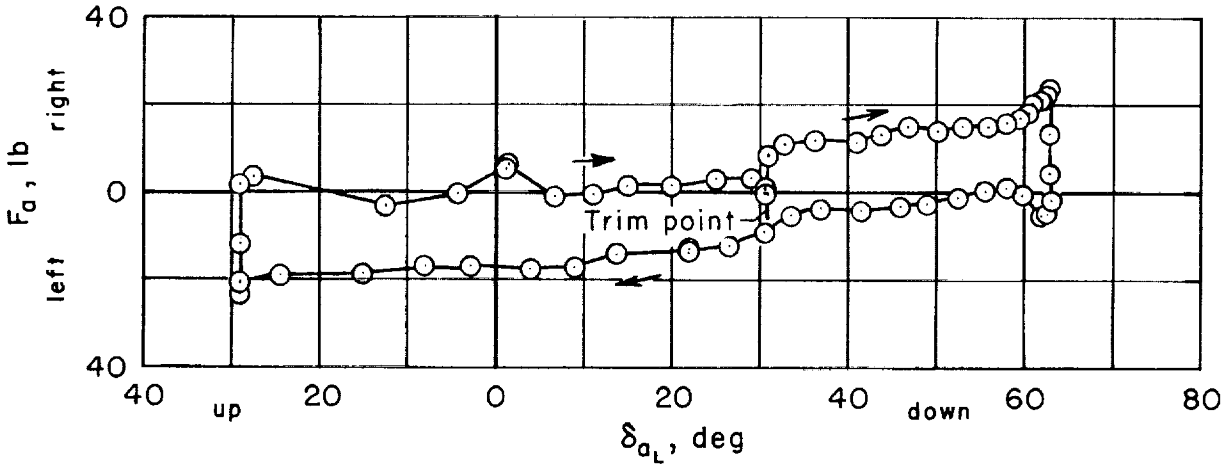


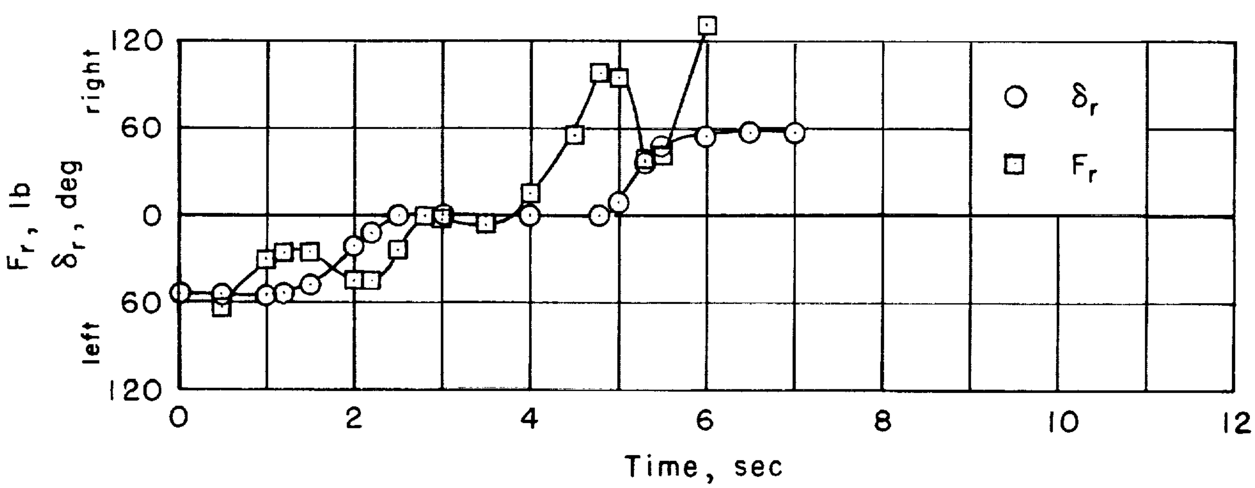
Figure 6.- Control power and damping.



(a) Elevator.



(b) Left aileron.



(c) Rudder.

Figure 7.- Mechanical characteristics of flight control system.

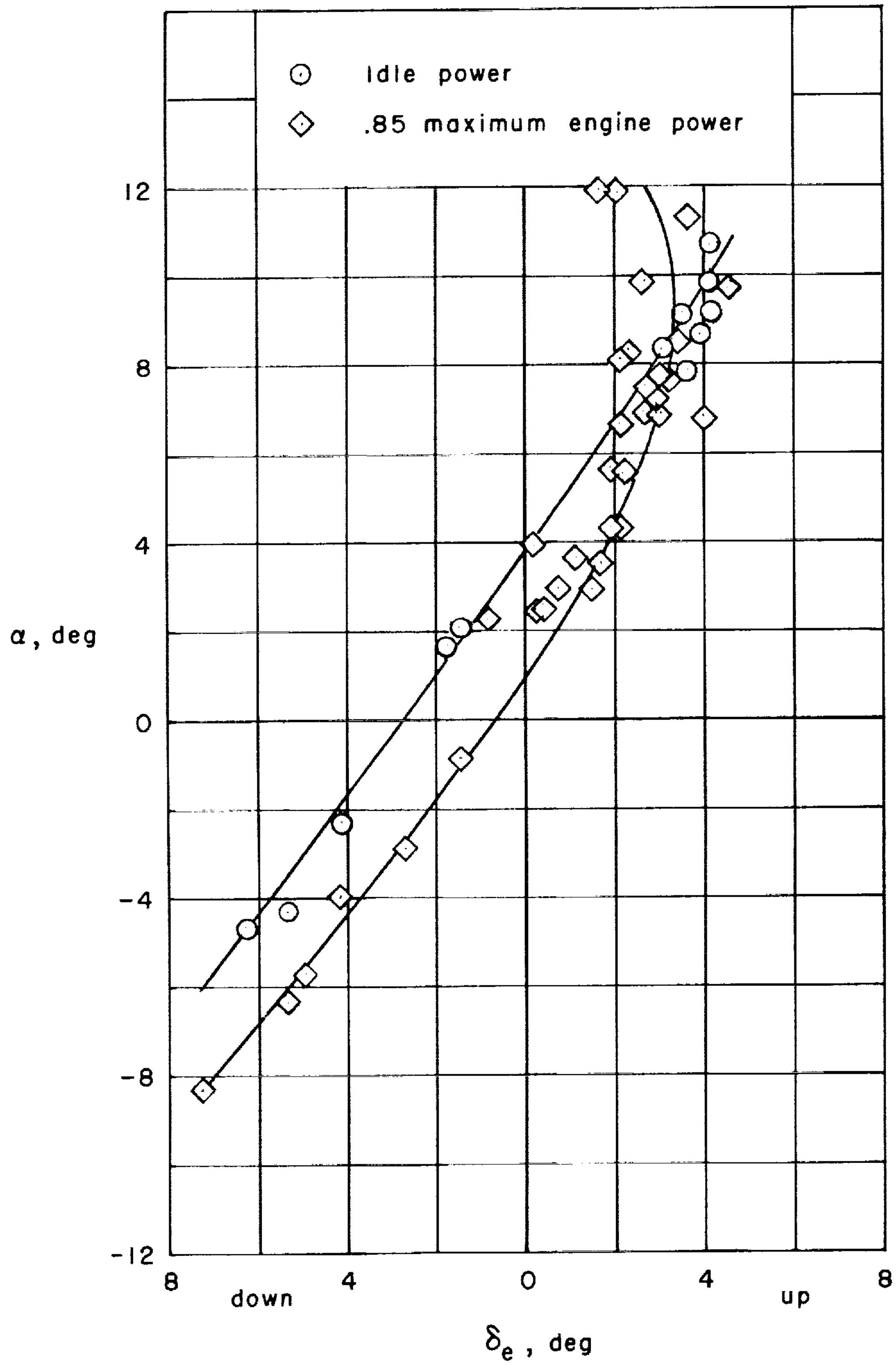
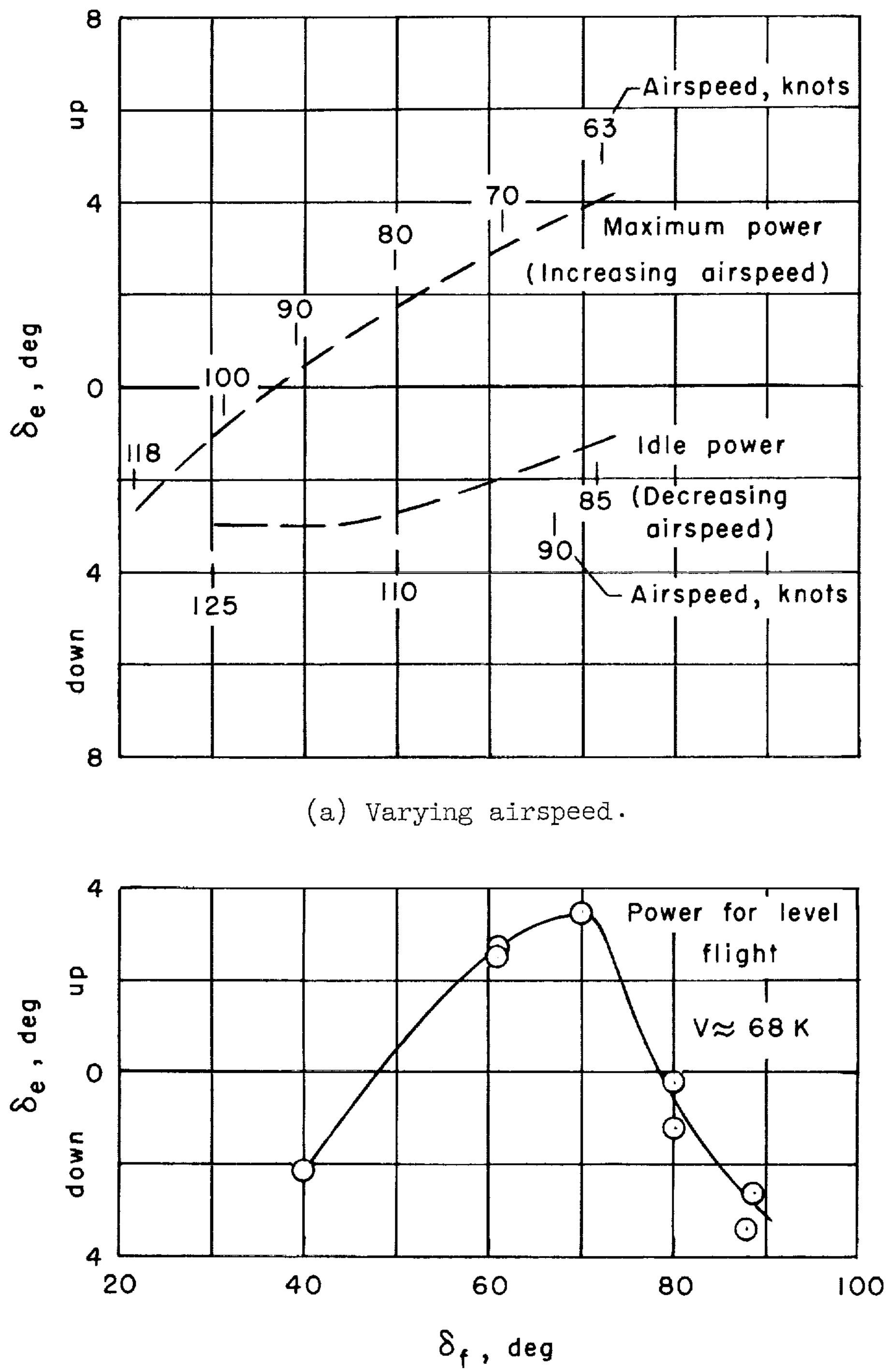


Figure 8.- Longitudinal static stability.



(a) Varying airspeed.

(b) Constant airspeed.

Figure 9.- Trim variation with flap deflection

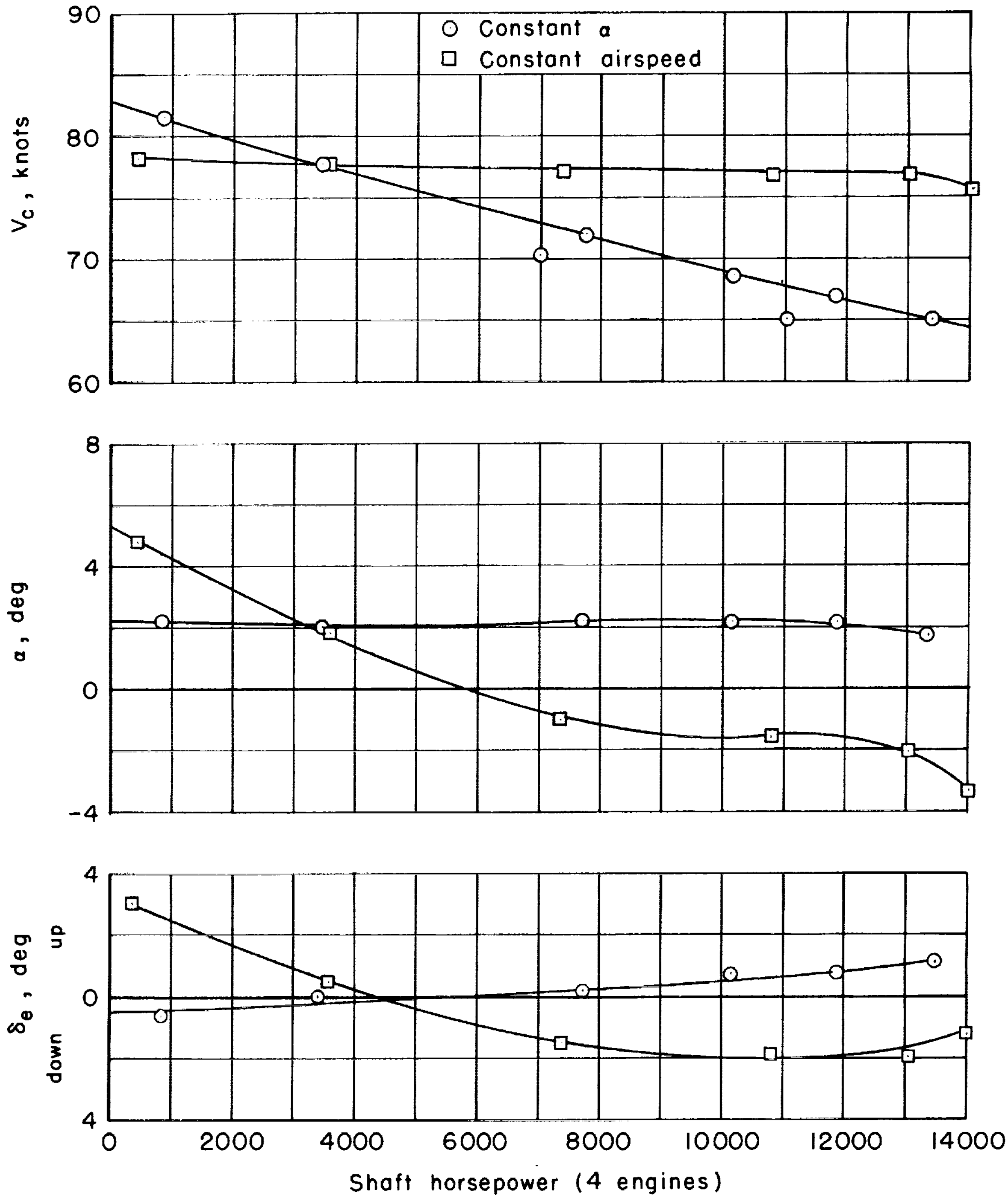


Figure 10.- Trim change with engine power.

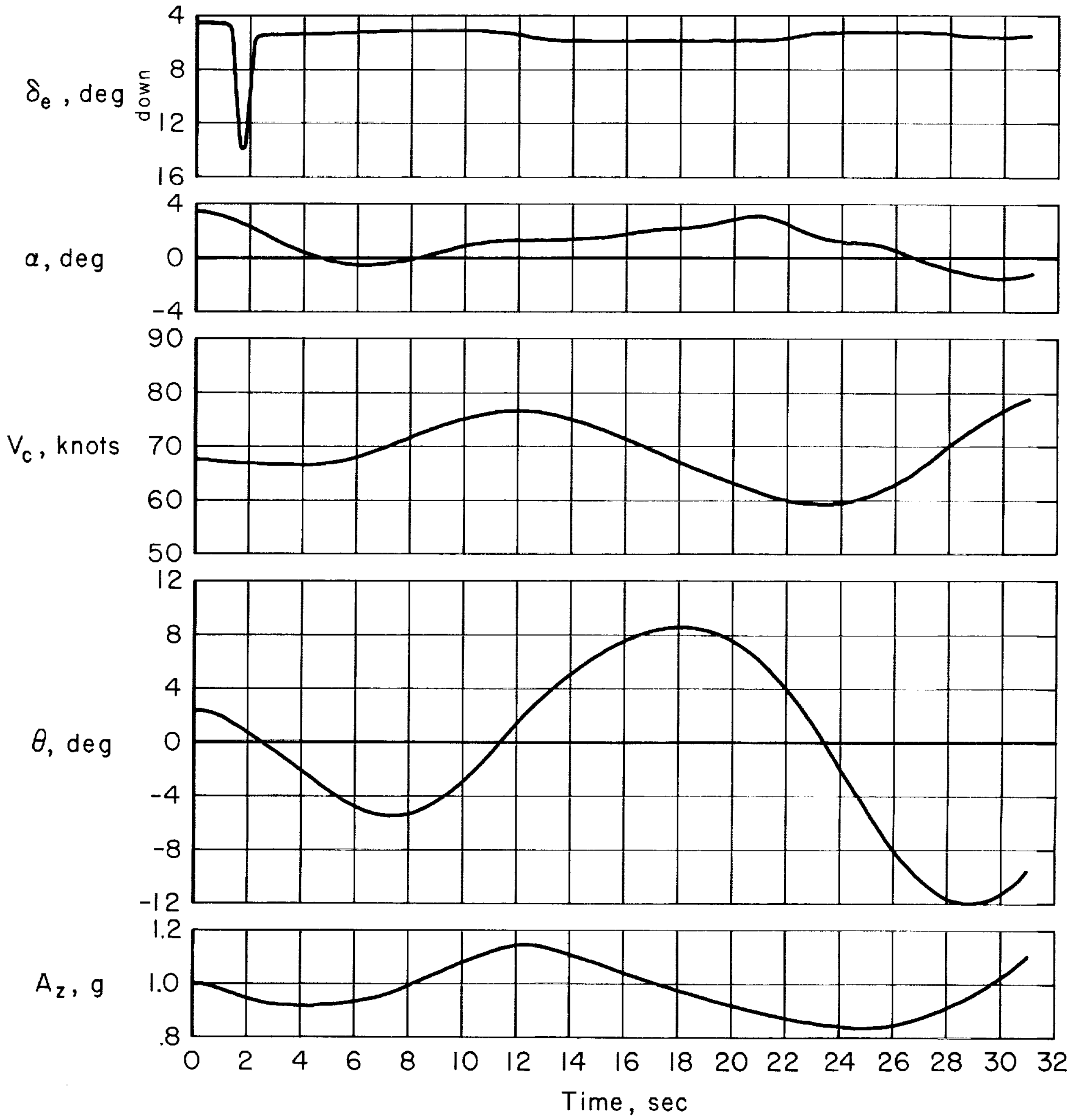


Figure 11.- Time history of the response to an elevator pulse; $V_c \approx 70$ knots.

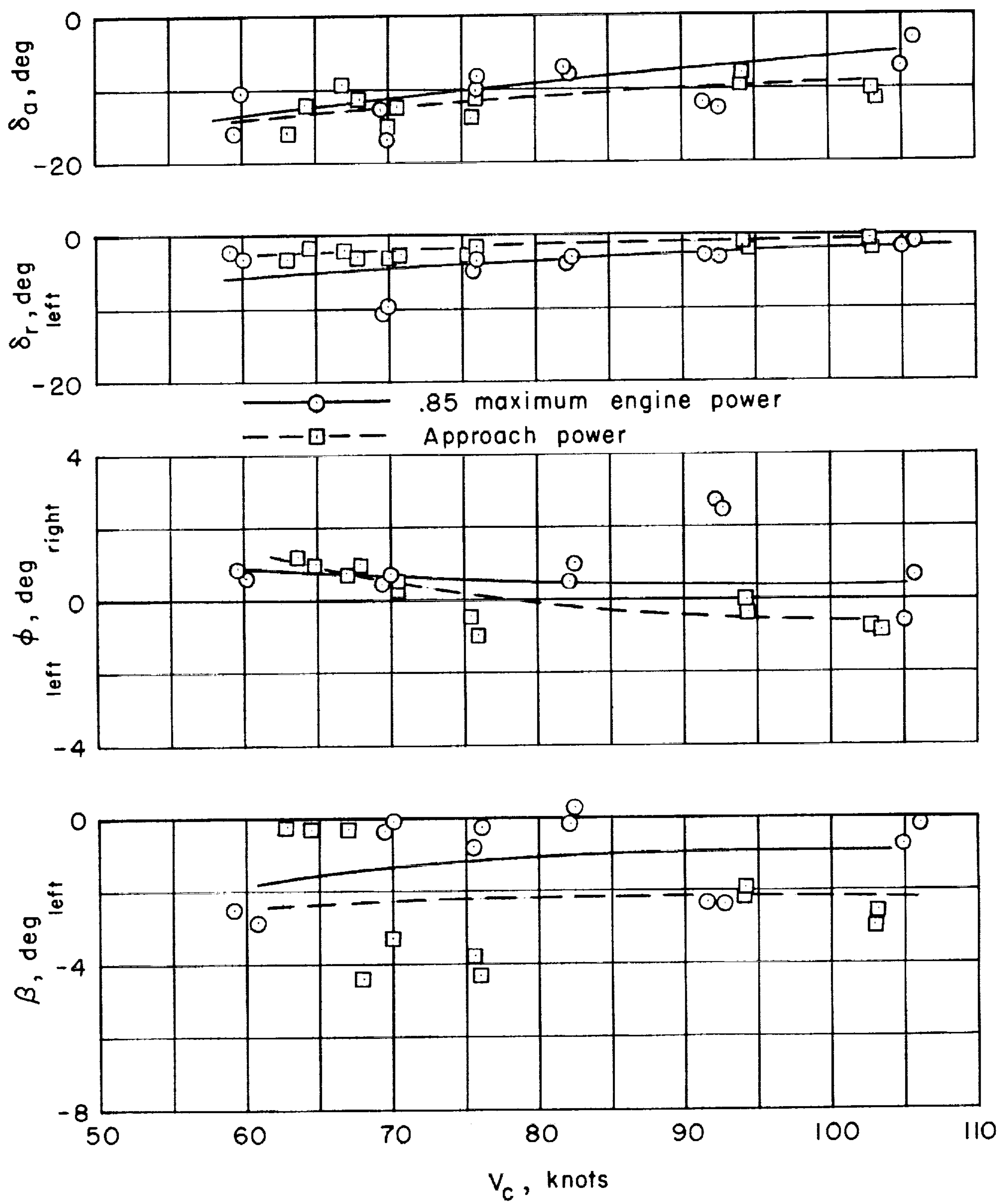


Figure 12.- Lateral and directional trim characteristics.

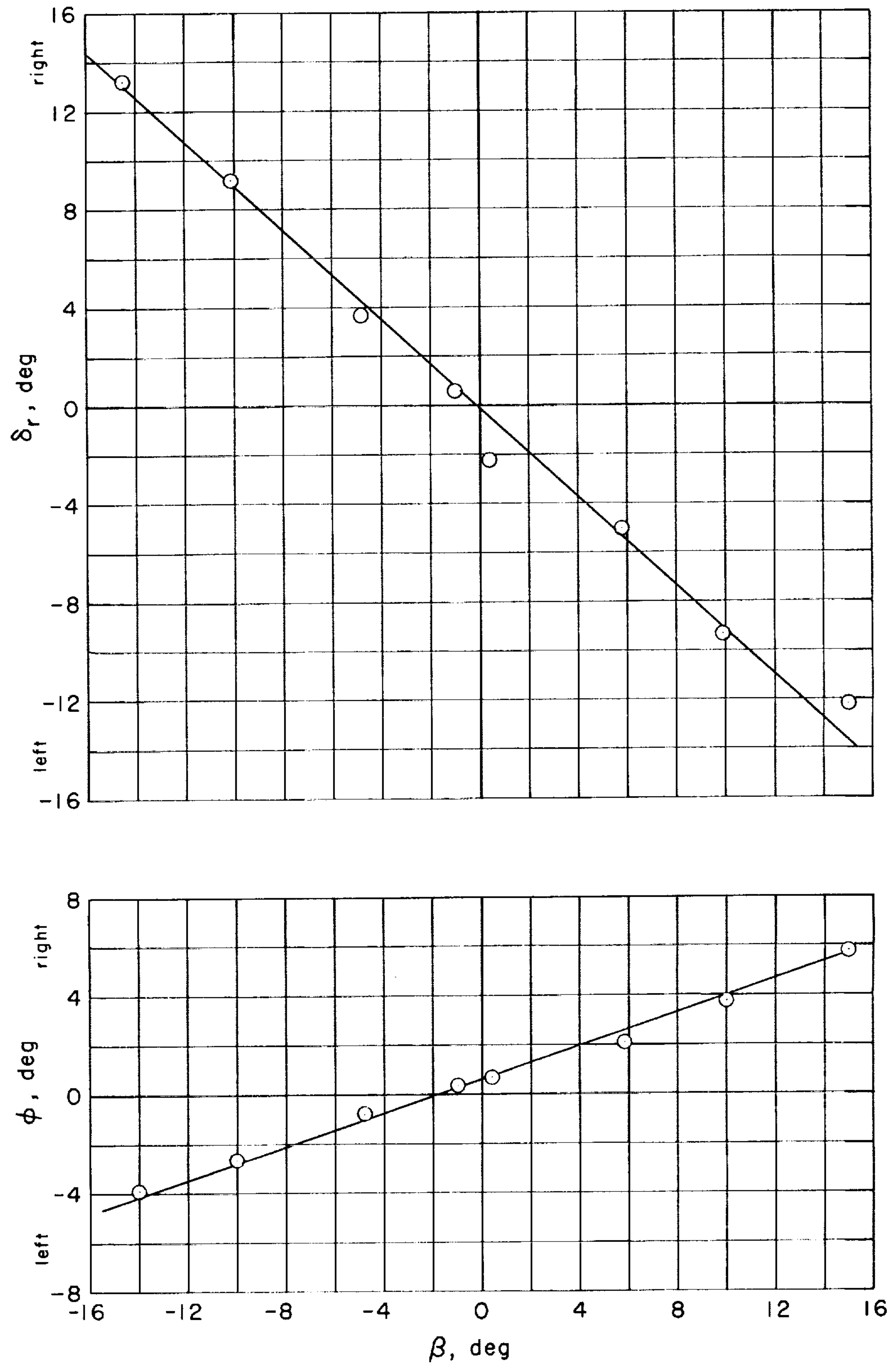


Figure 13.- Variation of rudder and bank angle required for steady state sideslips; $V_c \approx 70$ knots.

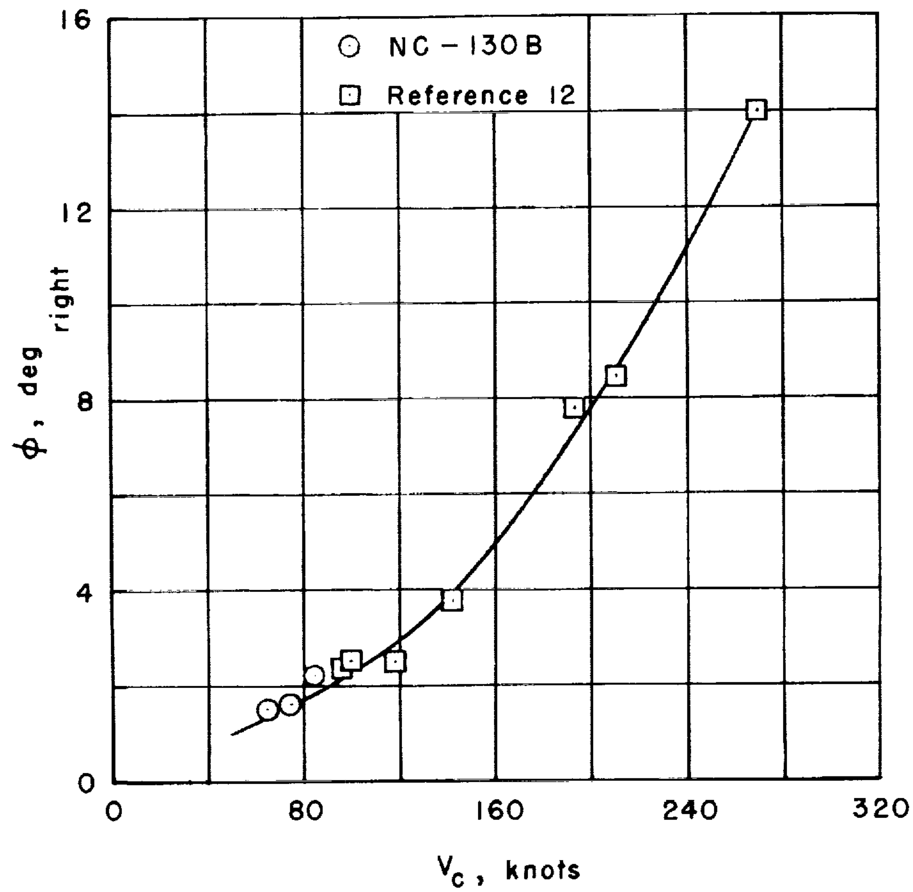


Figure 14.- Variation of bank angle with airspeed for 5° of sideslip.

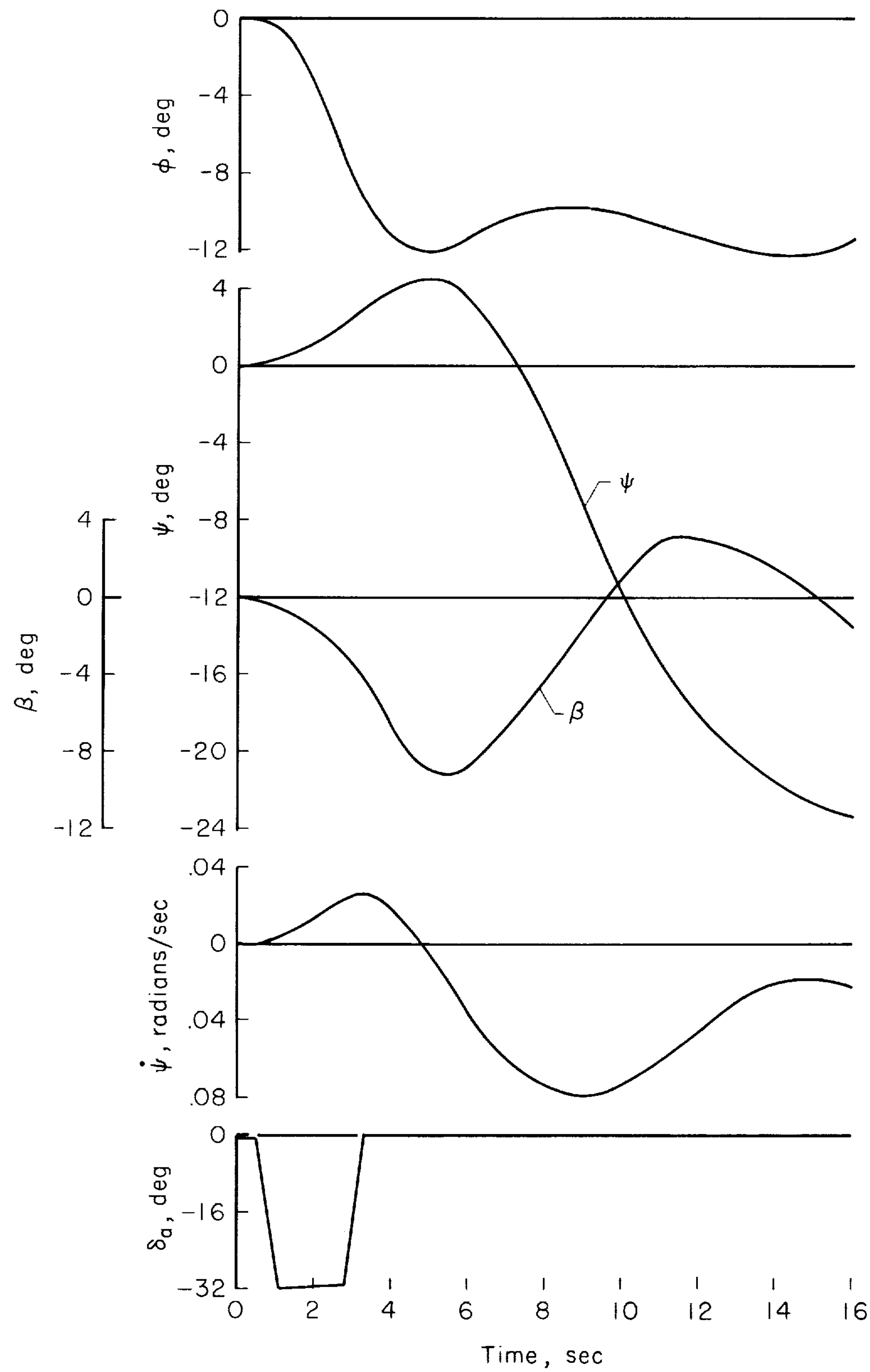


Figure 15.- Time history of the response to a lateral control input; $V_c \approx 70$ knots.

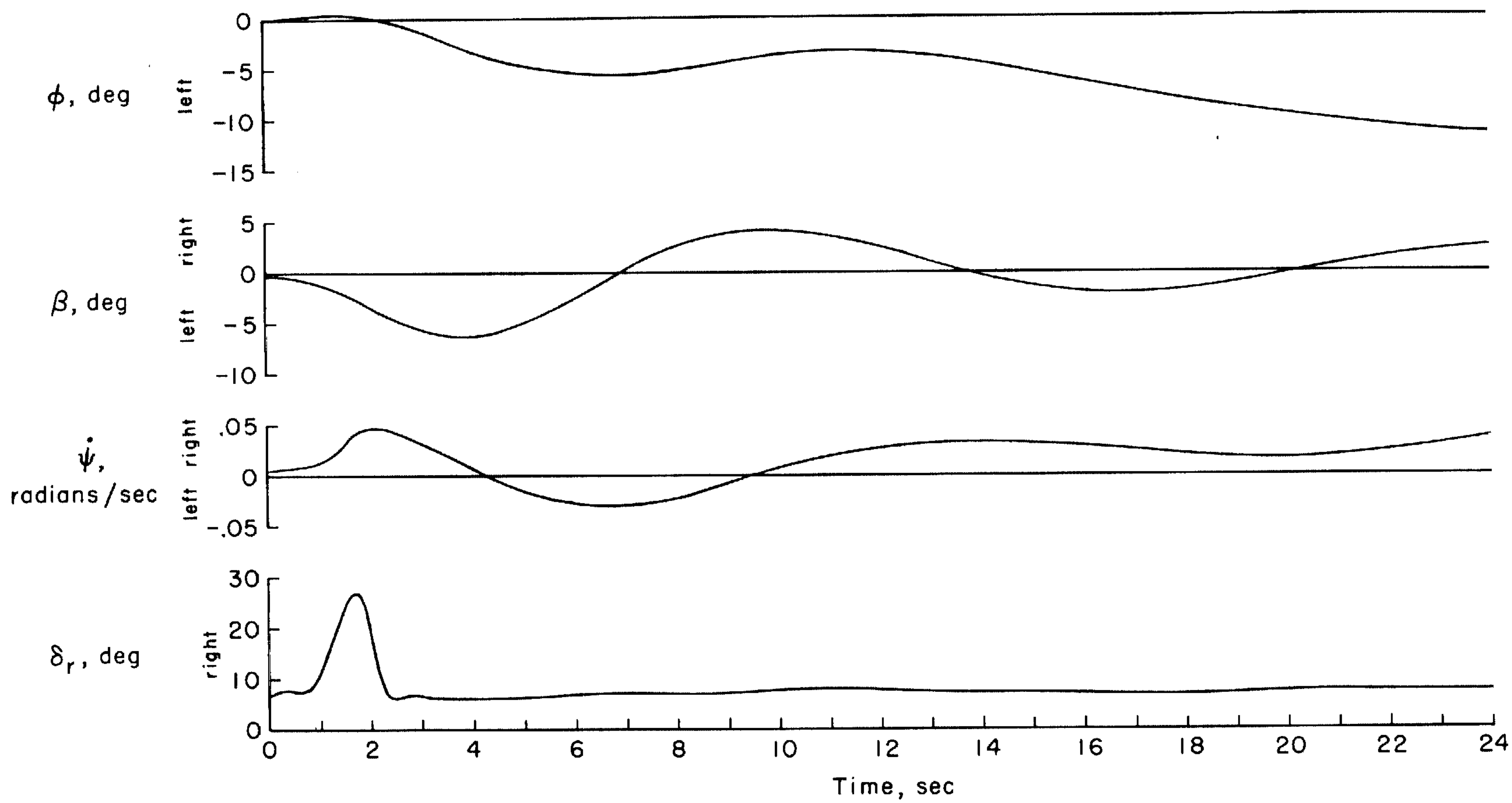


Figure 16.- Time history of the response to a rudder pulse; $V_c \approx 70$ knots.

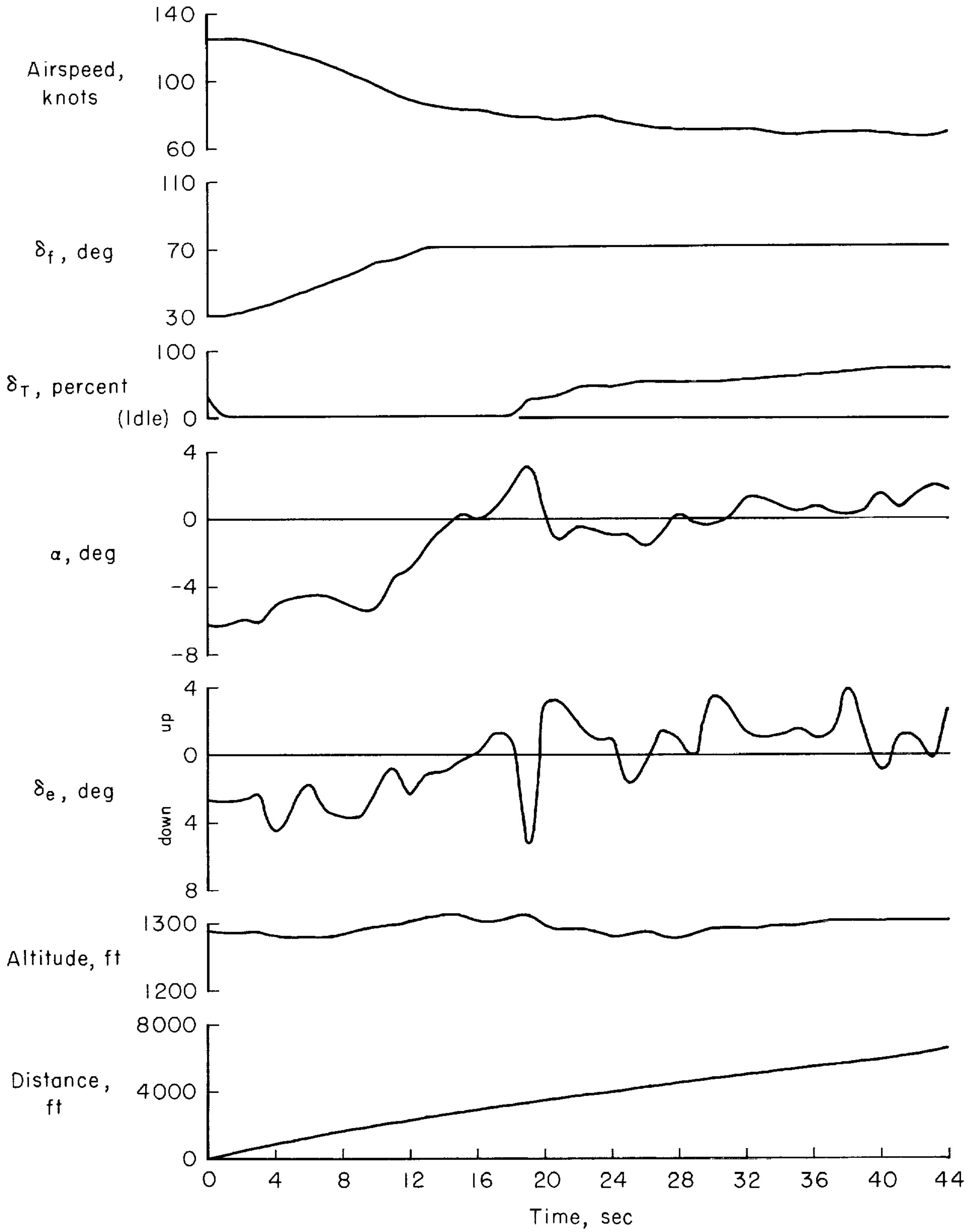


Figure 17.- Time history of lowering flaps and reducing airspeed.

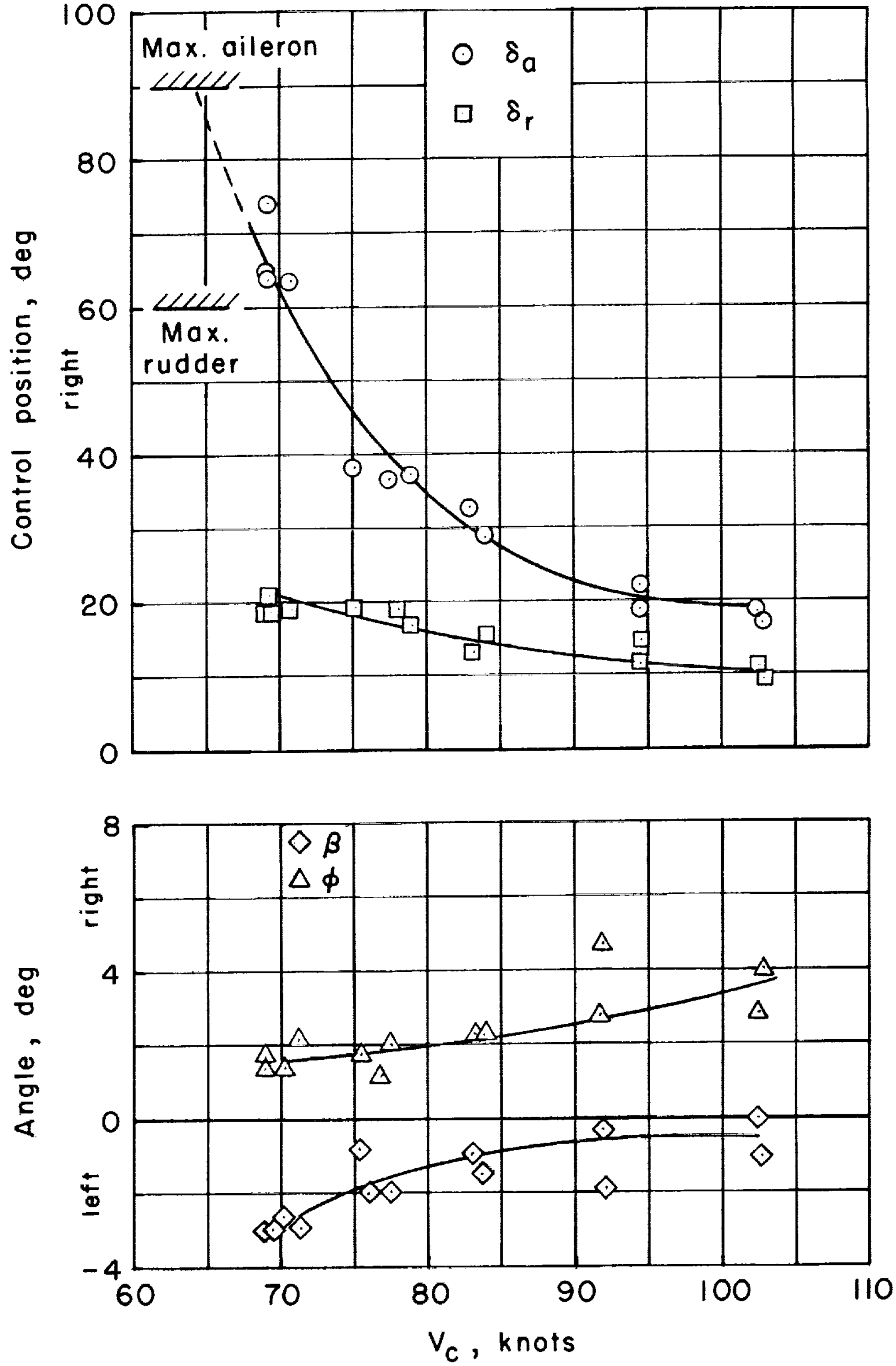


Figure 18.- Lateral and directional trim characteristic with critical engine out. (Left outboard engine windmilling all others at 2800 SHP.)

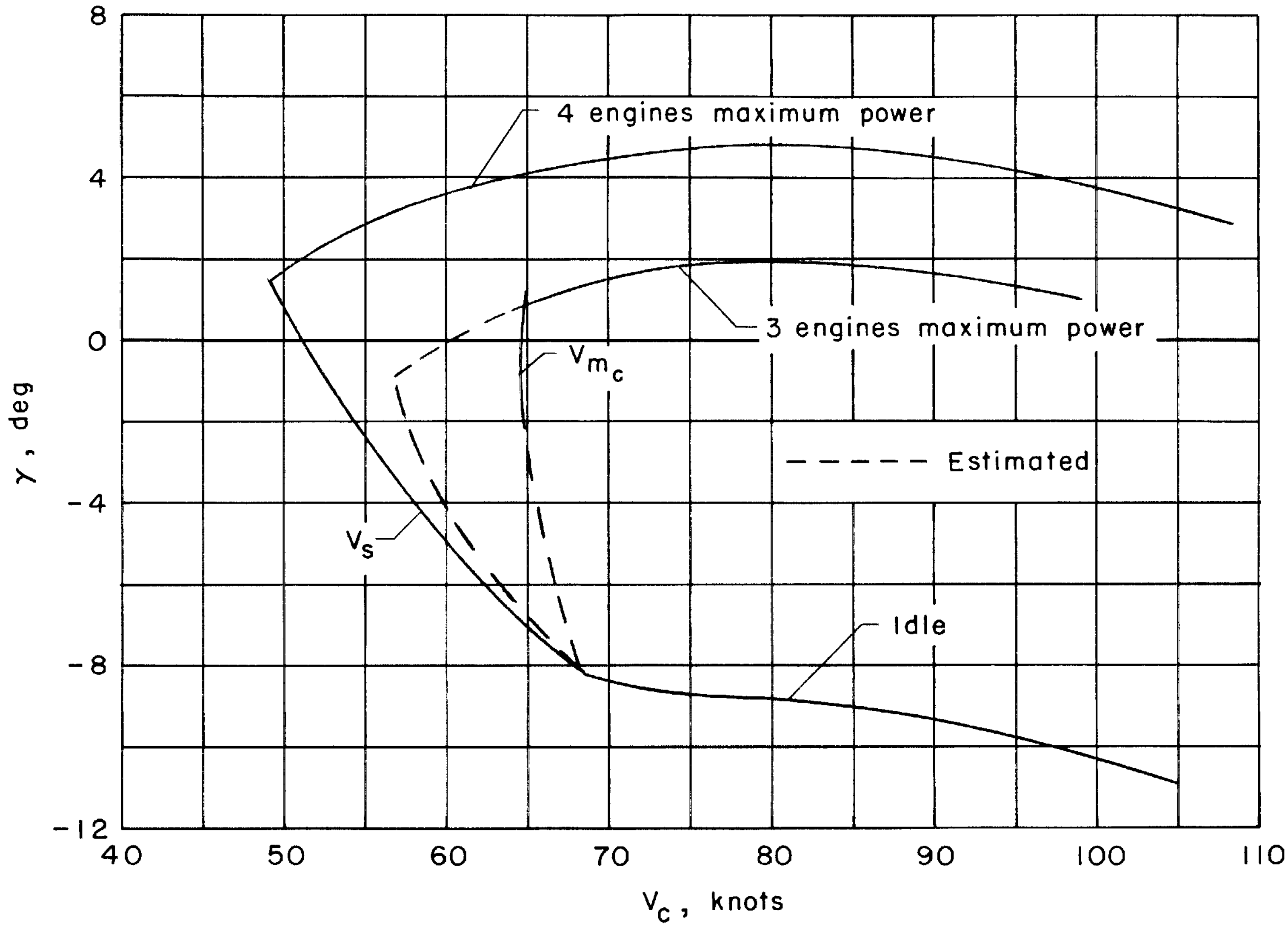


Figure 19.- Operational envelope with critical engine inoperative; $\delta_f = 70^\circ$, $\delta_{a_D} = 30^\circ$, BLC on.

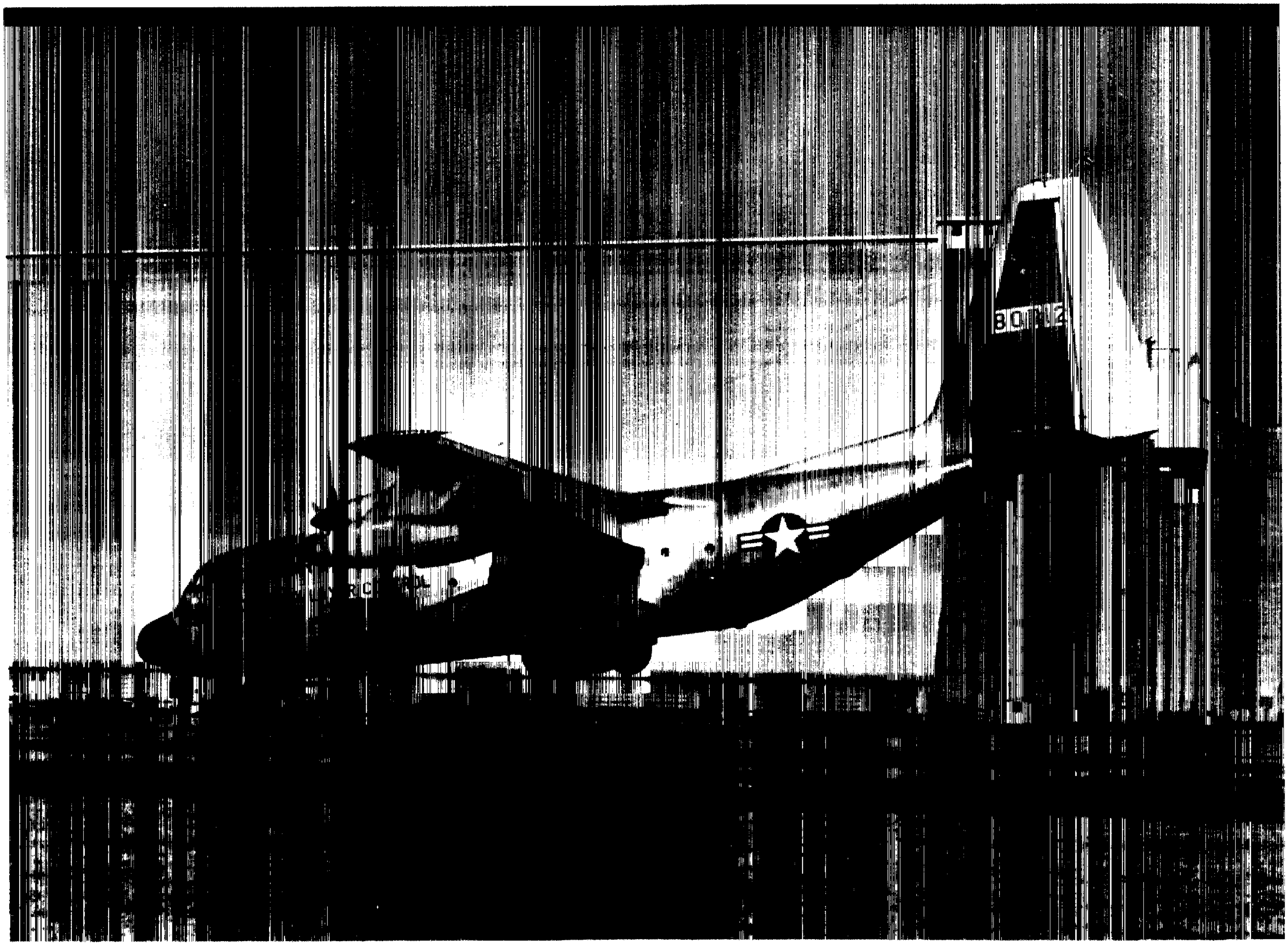


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Figure 20.- Photograph of airplane in level flight at 85 knots; $\delta_f = 70^\circ$ and $\delta_{a_D} = 30^\circ$, BLC on.

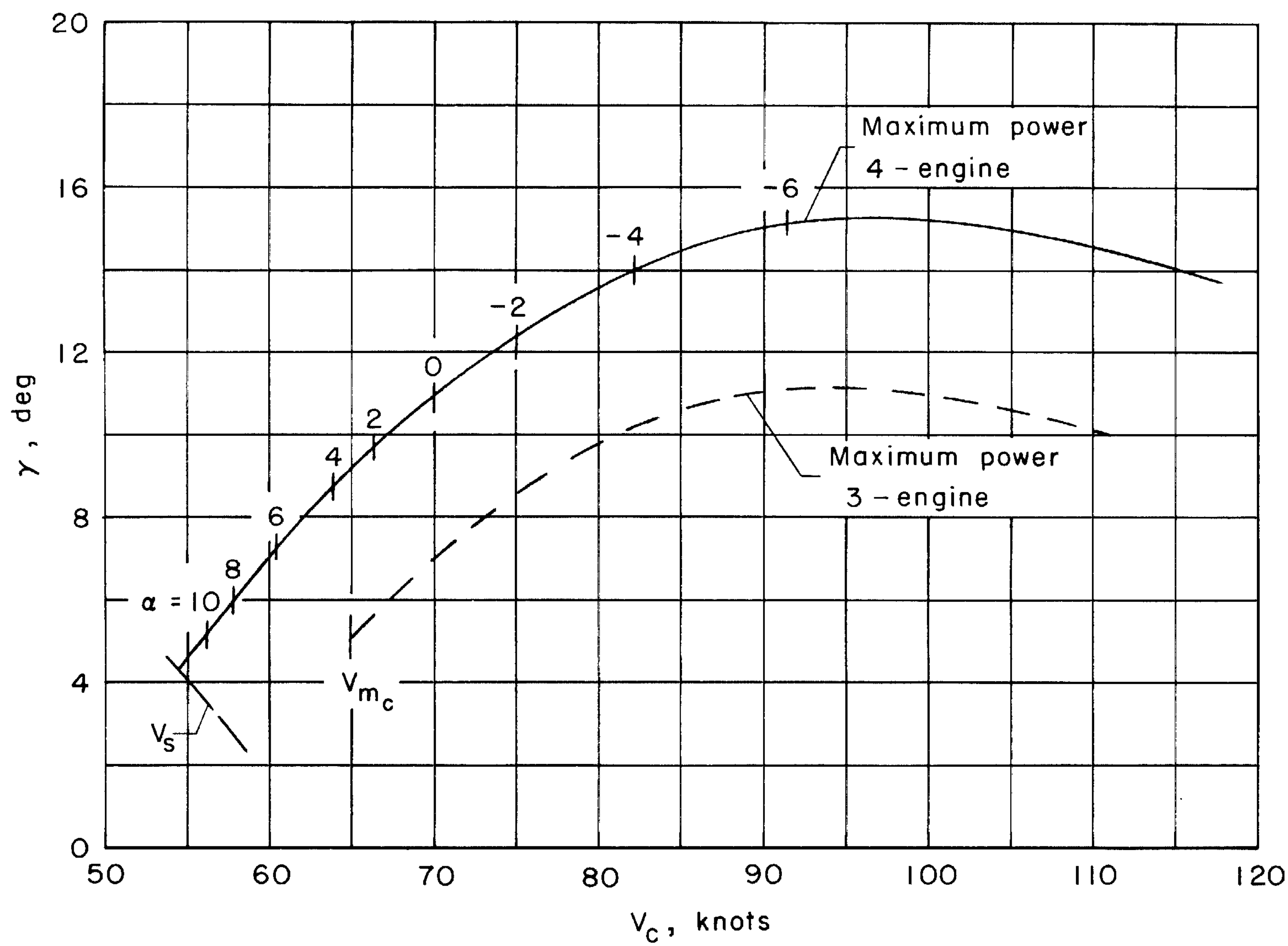


Figure 21.- Operational envelope in the take-off configuration; δ_f - 40°, δ_{a_D} = 30°, BLC on, gross weight = 106,000 lb., sea-level standard day.

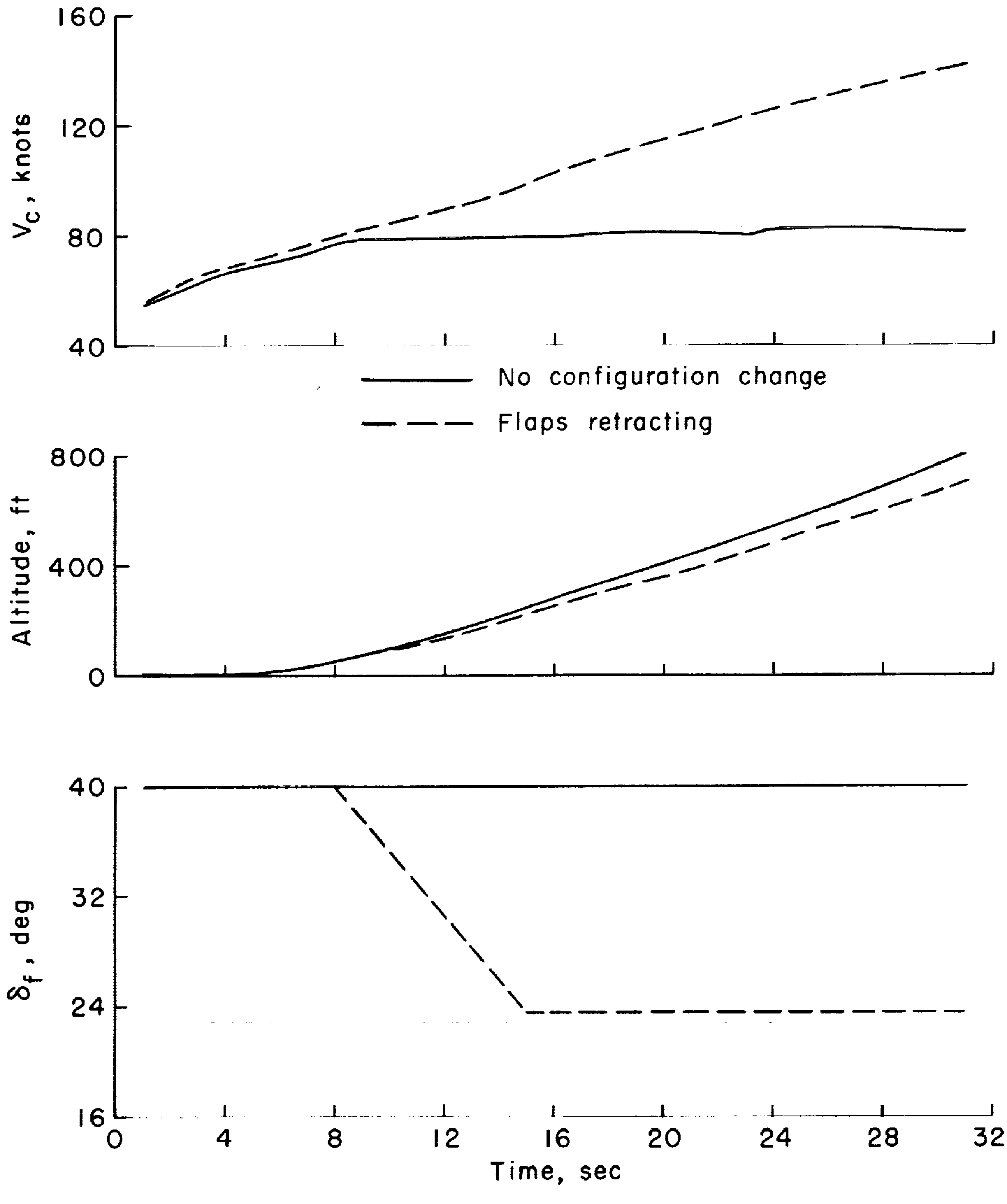
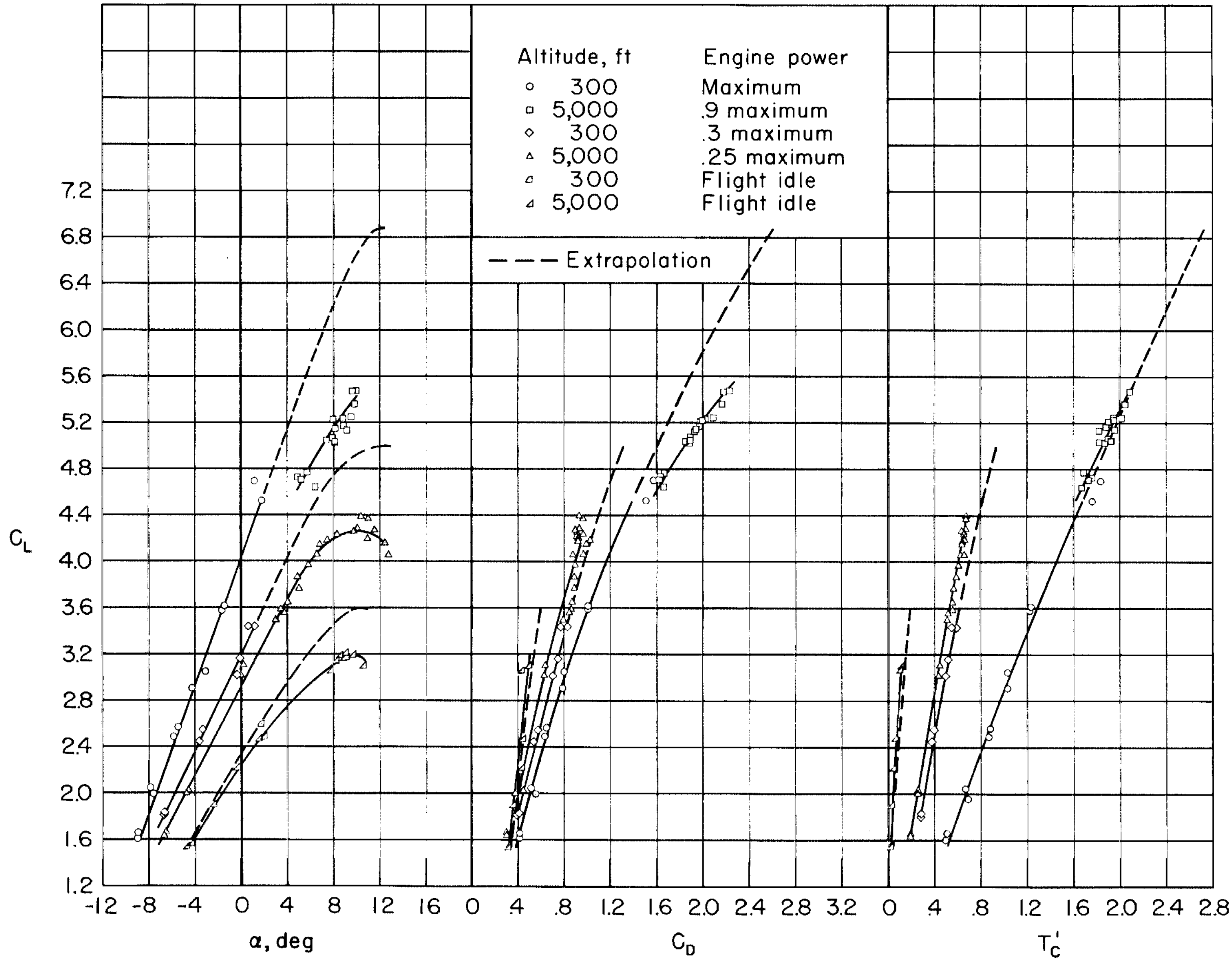
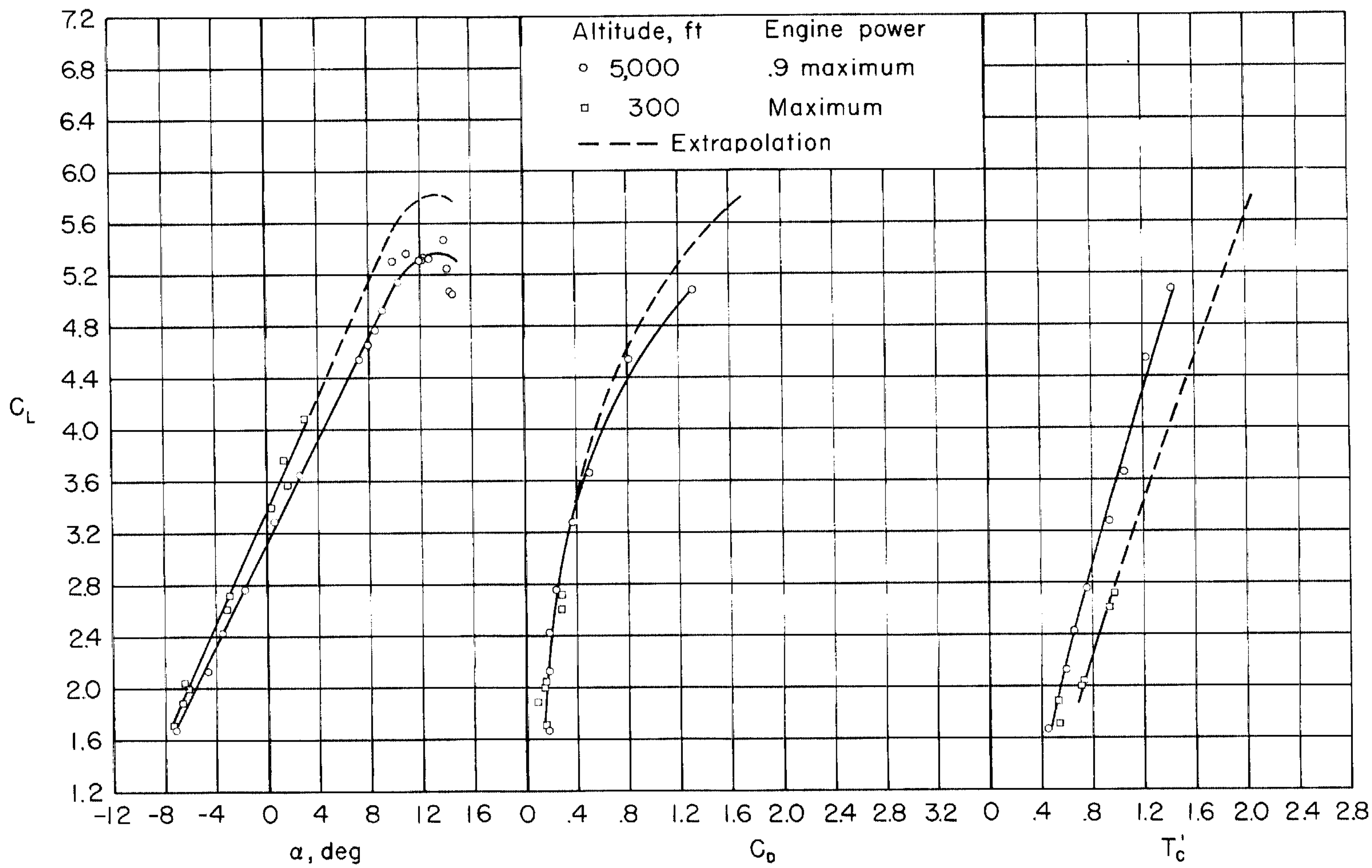


Figure 22.- Time histories of climb-outs, maximum engine power.



(a) Landing configuration; $\delta_f = 70^\circ$, $\delta_{a_D} = 30^\circ$, BLC on.

Figure 23.- Lift and drag characteristics in STOL configurations.



(b) Take-off configuration; $\delta_f = 40^{\circ}$; $\delta_{a_D} = 30^{\circ}$, BLC on.

Figure 23.- Concluded.

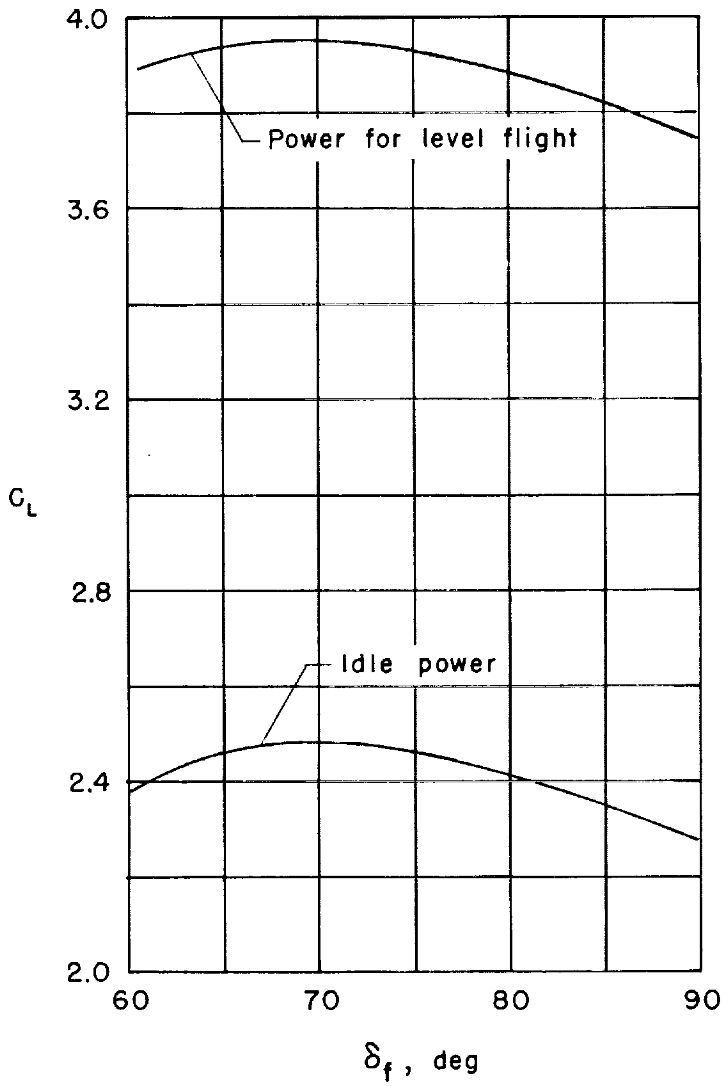


Figure 24.- Variation of lift coefficient with flap deflection at two engine powers; $\alpha = 2^{\circ}$.

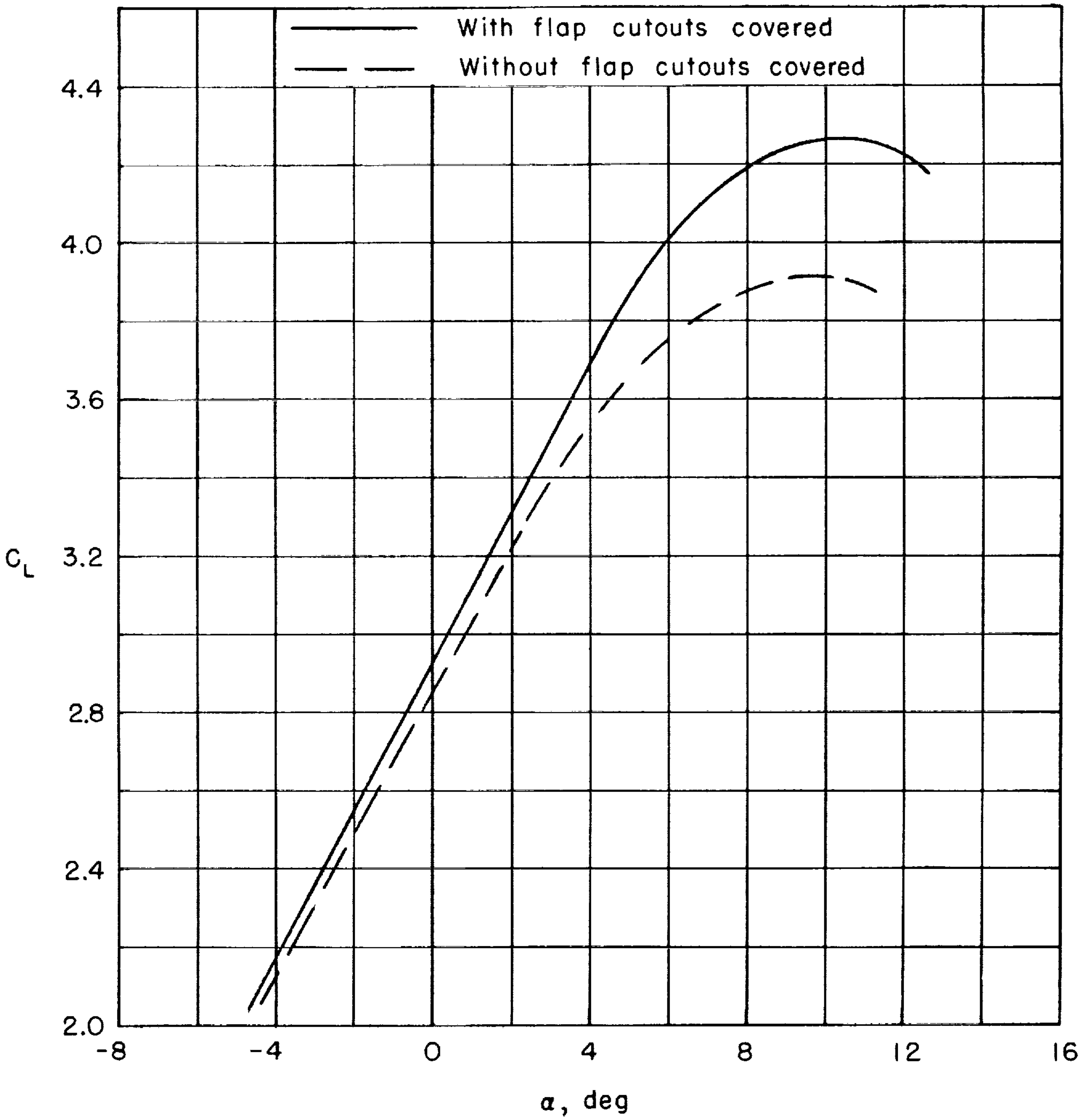


Figure 25.- Comparison of lift curves with and without flap cutout cover plates; $\delta_f = 70^\circ$, $\delta_{a_D} = 30^\circ$, BLC on, 0.3 maximum engine power.

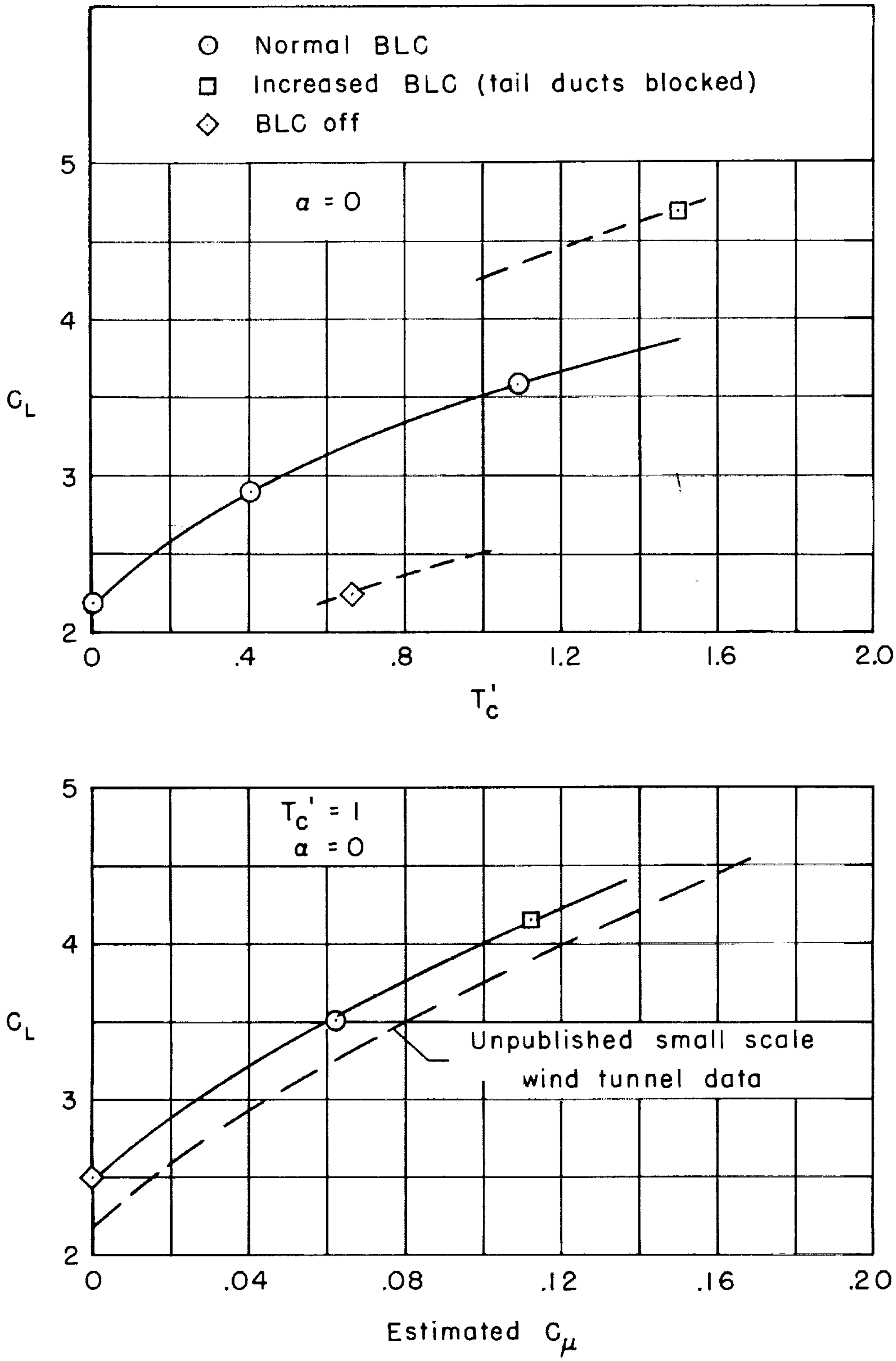


Figure 26.- Variation of thrust coefficient and momentum coefficient with lift coefficient.